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Use of waste glass powder toward more sustainable geopolymer concrete

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ABSTRACT

The influence of waste glass powder (WGP) with fly ash in certain proportions on geopolymer concrete (GPC) was investigated by exchanging different proportions of molarity and WGP percentages in GPC. For this objective, fly ash was altered with WGP having percentages of 10%, 20%, 30%, and 40%, and the effect of molarity of sodium hydroxide (NaOH) was examined. The compressive strength tests, splitting tensile tests, and flexural strength tests were conducted. The workability and setting time were also evaluated. With the addition of WGP, the workability for molarities (M) of 11, 13, and 16 NaOH reduced by an average of 17%, 10%, and 67%, respectively. The findings showed that the slump values decreased as the molarity and WGP percentages increased. Molarity significantly affected the setting time, but WGP had no effect on the setting time. Although high molarity increased the capacity, this had a noticeable negative effect on the setting time and workability. This study demonstrated that WGP had a slight negative effect on the capacity and workability. Furthermore, when the combined effects of WGP and NaOH molarity were taken into account, the use of 10% WGP with M13 NaOH was recommended to obtain the optimum sustainable GPC considering both fresh and hardening properties. Scanning electron microscopy (SEM) analysis was done on the samples, too.

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1. Introduction

A lot of energy is consumed during cement production and a large amount of CO_2 is released into the air. As a result, it causes serious environmental problems. Therefore, alternative materials such as cement additives are attracting the attention to reduce cement production. In addition, due to the development in the world, the resources are reducing, and manufacturing trashes are growing. It is seen in the studies

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that these circumstances reason serious ecological complications. Scientists, who are aware of the environmental problems caused by cement production and industrial wastes, offer alternative construction element suggestions for the construction industry to consume less raw materials and for the permanent evaluation of wastes. Recycling industrial waste materials reduces raw material usage and costs. Cement has been expended in the literature since ancient times. However, the use of cement makes a large quantity of greenhouse gas emissions that cause global warming. These problems have created a research area for today's engineers who are investigating possible alternatives to produce environmentally friendly concrete. Therefore, alternative environmentally friendly materials are needed for these additives [1–5].

There are many industrial and organic wastes such as steel slag, marble, ceramic, glass, fly ash, etc. [6–19]. The use of these types of waste materials decreases the utilization of raw materials [20–24]. At the same time, glasses produced day by day also cause an increase in the quantity of waste glass. Increasing wastes can create problems in landfills. In order to minimize these problems, waste glass dust can be evaluated in the construction industries and expended in concrete production for replacing cement. The implementation of waste glass powder (WGP) as an aluminosilicate precursor in geopolymer concrete (GPC) prepping has been explored for the last two decades as an option to eco-friendly building material thanks to its great effect on reducing greenhouse gases. Instead of cementitious concrete, GPC comes as an alternative [5,25–28].

Kumar et al. [5] aimed to produce GPC at room temperature. Fine aggregate (M-Sand) with WGP varying by 5%, 10%, 15%, and 20% was utilized for replacement. Bharathi et al. [25] studied concrete with 20 MPa strength using 20% WGP and fine aggregate, and steel slag in varying amounts of 25%, 50%, and 75% instead of cement. Manikandan and Vasugi [29] evaluated the implications of varying amounts (25–40%) of WGP on the penetrability and mechanical features of GPC obtained with a fixed percentage (10%) of metakaolin and ground granulated blast-furnace slag (GGBS). The results showed that the optimum WGP ratio in GPC was detected as 35%. Najaf and Abbasi [30] did mechanical tests on prepared samples using waste glass and plastic powders in ordinary Portland cement (OPC). Jiang et al. [31] experimentally analyzed the effect of using OPC addition, WGP, on their samples after exposure to ambient temperature and high temperatures and considered the physico-mechanical features such as the penetrability, setting time, and compressive strength (CS) of OPC samples containing WGP (0, 10%, 20%, and 30%) in different mass contents. Derinpınar et al. [32] created 5 different GPC mixtures by replacing 0.5%, 10%, 15%, and 20% by weight of slag with WGP. Two recycled materials, WGP and F class fly ash (FF), were expended as raw materials in the prepping of GPC by Xiao et al. [33], and they added WGP as 0% and 10%, and fly ash as 0% and 10%. Tho-In et al. [34] replaced 10%, 20%, 30%, and 40% by weight of fly ash with WGP to produce GPC. Four different WGP percentages were chosen for metakaolin-based GPC by Si et al. [35], which were 0%, 5%, 10%, and 20% of the total weight. Metakaolin-based geopolymers have had their permeability enhanced by the addition of WGP and glass particles, because of their low surface area and relatively smooth surfaces which could help increase the permeability by lowering the amount of water needed to wet the solid mixture. Jiang et al. [36] prepared GPC at 0%, 10%, 20%, and 30% WGP. Sethi et al. [37] aimed to develop GPC cured under ambient conditions. 15%, 20%, and 25% fly ash were replaced with GGBS, and 5%, 10%, and 15% WGP were added and cured under ambient conditions.

Adesina et al. [38] assessed the fresh and mechanical features of GPC made with WGP and alkali-activated materials. The findings demonstrated that the incorporation of alkali-activated materials into WGP provided good results with an improvement in the penetrability and a prolongation of curing times. Good results were obtained at low molarity values in CS of GPC formed with sodium hydroxide (NaOH) and WGP. Aisheh et al. [39] assessed NaOH with molarity (M) dosage varying from 6 to 14 (M6, M10, and M14), and sodium silicate (Na_2SiO_3) per NaOH, Na_2SiO_3/NaOH, from 1.5 to 3.5. Aisheh et al. [40] investigated the effect of different molarities, alkaline/binder (A/B), and Na_2SiO_3/NaOH on the improvement of fresh and mechanical features of GPC. They also set out to explore the latest trends and technology regarding developments in GPC in recent years. A/B of 0.30–0.5 and M5, M8, and M18 were compared. WGP and FF were combined (1:1 by weight) together with an alkaline activator consisting of M5 NaOH dispersion to Na_2SiO_3 dispersion (1:2.5 by weight), as described by Xiao et al. [33]. Using M12 NaOH dispersion as an alkaline activator, Derinpinar et al. [32] cured GPC samples in the laboratory. Active dispersions of NaOH and Na_2SiO_3 were used by Tho-In et al. [34]. M12 NaOH dispersion was made. Na_2SiO_3 was utilized instead of NaOH, and A/B was 0.6. Dipten et al. [41] used a lot of WGP and an alkaline activator based on sodium. Samples of alkali-activated mortar with NaOH concentrations of M6 and M8 were poured, and the liquid was used up in the process. A/B was determined to be 0.55% Na_2SiO_3 dispersion, 2.5% NaOH dispersion, and M2-M12 NaOH dispersion by Manikandan and Vasugi [42]. Working at several molar concentrations, Sethi et al. [37] measured the impact of M4, M8, and M12 on the created mixes, and then decided on the optimal molarity concentration for the manufacture of the mixtures.

It was stated that the mechanical features improved as molarity increased. The splitting tensile strength (STS) and flexural strength (FS) were 35% using NaOH dispersion at M12 concentration. They mentioned that CS, STS, and FS enhanced by 20.95%, 17.05%, and 24.44%, respectively, compared with conventional concrete [34]. According to [29], CS and FS of GPC were almost equal to CS and FS of the cement concrete samples. The obtained results illustrated that the optimum substitution of 50% of fine aggregate in combination with 20% WGP improved the penetrability. CS, FS, and STS were examined using microsilica and GGBS containing ultra-high-performance GPC (UHPGPC), polypropylene fiber, and steel fiber. The penetrability decreased as the fiber dose increased. NaOH was assessed with M6, M10, and M14, and it was concluded that increasing the NaOH dosage from M6 to M14 and Na_2SiO_3/NaOH from 1.5 to 3.5 increased CS of the UHPGPC samples [39]. It was revealed that the addition of WGP contributed to the penetrability, but the OPC mix led to a longer curing time. On the other hand, it was reported that the inclusion of WGP in OPC made OPC to

be more resistant to high temperatures. In addition, WGP additives were explained according to the test results, which extended the initial setting time of the OPC mixture [31]. With the increase in the molarity concentration, the precipitation values decreased. Mechanical properties at 7, 14, and 28 days increased with the molarity concentration. Maximum mechanical properties were detected at M16–M18. They expressed when A/B was 0.35, maximum STS and FS were detected [34]. Compression and California Bearing Ratio (CBR) tests displayed positive results which can be preferred as a road pavement material [33]. The samples were kept at different temperatures for 1 h and their CS, weight change, and sorptivity values were obtained. They concluded that as the WGP percentage increased, the mechanical features of GPCs decreased. However, it was suggested that there is an increase in the performance of GPCs exposed to high temperatures [32]. It was stated that the samples were cured at around 60 °C for 2 days and kept at constant temperature 23 ± 2 °C until testing. CSs were found to be between 33 MPa and 48 MPa, or about 73–104% of the reference mixture. It was explained that as the WGP content increased, CS reduced [34]. It was mentioned that the initial and final setting times were prolonged with the increase of the WGP content in the mixtures. However, CS decreased with increasing the WGP content in the mixture [35]. WGP enhanced the penetrability, and the optimum CS was obtained from the mixture with 20% WGP [36]. The mixture was cured for 72 h at a high temperature of 65 °C. When the results of fly ash and WGP geopolymer binders were examined, as expected, M8 activator-based geopolymers demonstrated superior CS compared with M6 activators [41]. The findings they obtained about the use of WGP in GPC are as follows. In geopolymer binder prepping, partial replacement of WGP with aluminosilicate source materials between 20% and 30% improved CS, and further increasing the WGP percentage caused brittle structure, less reactivity, and high-volume alkalinity. It reduced CS due to the formation of WGP, combining WGP (0–15%) with other source materials in the production of geopolymer, and increasing STS. But, it led to a significant drop in STS values. The optimum percentage of WGP providing maximum FS is limited to 30% in the literature. They stated that increasing WGP by more than 30% has a negative effect on FS of GPC [36]. The control combination with only fly ash had less strength than all other mixes with higher molarity concentrations (M8 and M12) for the same GGBS percentage change [37]. WGP and alkaline dispersions were applied, and better CS was found for the alkali-activated mixture. High strength concrete with WGP was developed and very high CS up to 234 MPa was achieved. It was indicated that the improvements in the mechanical features of GPC are related to the curing times of concrete. The best CS was obtained from concrete using 20% WGP instead of cement [43–46]. In a study on the effects of WGP with geopolymer and molarity of NaOH on the mechanical features of geopolymers, it was pointed out that curing methods were more important than molarity of NaOH. A value of 14 MPa was obtained after 28 days of curing 37.5% WGP (by weight). The use of 20% WGP in the mixture of fly ash, WGP, and GGBS achieved higher CS. Better CS and STS were obtained for 15% and 10% of fly ash and WGP [47–50]. Major findings of the literature are summarized in Table 1.

As mentioned above, there are several investigations about the performance of GPC with the molarity and WGP percentages in the literature. However, insufficient studies realized the impacts of different proportions of the molarity and WGP percentages on GPC. Additionally, there are very partial investigations about their influence on GPC. Therefore, unlike previous studies, in this study, ratio of fly ash to WGP was

Table 1 – Summarized major findings of the literature.

Studies	Content of WGP	Molarity of NaOH	Major Findings
Kumar et al. [5]	5–50%	–	For 50% WGP replacement, a maximum FS of 6.85 MPa and a maximum STS of 5.21 MPa were obtained.
Bharathi et al. [25]	20%	–	CS, STS, and FS increased by 20.95%, 17.05%, and 24.44%, respectively, compared with conventional concrete.
Manikandan and Vasugi [29]	25–40%	M2– M12	CS and FS of GPC were almost equal to CS and FS of the cement concrete samples.
Najaf and Abbasi [30]	0, 10%, 20%, and 30%	–	WGP is a sustainable cement alternative that may be utilized at 20% of its weight without affecting concrete's CS and FS.
Xiao et al. [33]	0–10%	M5 NaOH	Compression and CBR tests revealed positive results and can be preferred as a road pavement material.
Tho-In et al. [34]	10%, 20%, 30%, and 40%	M12 NaOH	CS was found to be between 33 MPa and 48 MPa, or about 73–104% of the reference mixture. CS decreased as WGP increased.
Jiang et al. [36]	0%, 10%, 20%, and 30%	M10 NaOH	WGP enhanced the penetrability, and the optimum CS was obtained from the mixture with 20% WGP.
Sethi et al. [37]	5%, 10%, and 15%	M4, M8, and M12	The control combination with only fly ash had less strength than all other mixes with larger molarity concentrations (M8 and M12) for the same GGBS percentage change.

changed with WGP having ratios of 10%, 20%, 30% and 40% and the influence of molarity of NaOH was also examined. The molarity value of the NaOH dispersion in this study was established as 11, 13, and 16. NaOH between M6-M18 has been used in the literature. Studies showed that as molarity increased, mechanical properties such as CS and FS enhanced, while the workability and setting time decreased. In previous studies, M12 was preferred. In this research, both very good mechanical performance and workability were aimed with M13. There is an expectation of a useable concrete class even with M11 NaOH. It is expected to lead to good results in terms of mechanical performance with M16 NaOH. Not only the effects of molarity of NaOH, but also the effects of replacing WGP with fly ash in certain proportions were investigated here, unlike many afore-said studies in the literature. As a result, this study provides various important supports to the literature. Details of the current study are presented in the following sections.

2. Materials and method

This study aims to develop economical and sustainable composite GPC using a variety of waste materials. It was conducted by replacing WGP with fly ash in certain proportions. The molarity value of the NaOH dispersion expended in the study was considered as 11, 13, and 16. Many studies have been done on the penetrability, setting time, and strength features of GPC. In addition, in the current study, the effect of WGP on GPC was examined. For this purpose, while the percentage of fly ash to WGP was kept constant and the percentage of molarity of NaOH in the mixture was changed as 11, 13, and 16. Furthermore, the percentage of fly ash to WGP was taken as 0%, 10%, 20%, 30%, and 40%, whilst the value of molarity of NaOH was 11, 13, and 16 in the concrete mixture. Fifteen mixes were designed, including the reference. The use of WGP in GPC is an important issue for sustainable environmental practices. The strength, penetrability, and setting time were assessed depending on Na_2SiO_3/NaOH and NaOH concentration. The NaOH molarity value was concluded by considering the above studies. According to the study of Adesina et al. [38], lowering this percentage increases the penetrability, but decreases the strength. A higher molarity can enhance the strength but makes problems for the penetrability.

The fundamental source material of GPC is fly ash, 90% of the particles are smaller than 45μ, and is coal-based, which was purchased from a company in Turkey. WGP expended in the experimental study was supplied having 98% pure NaOH, 50% pure Na_2SiO_3, 7–11 mm coarse aggregates, and 0–2 mm grain diameter Rilem sands which were expended as fine aggregates. The size of WGP expended in this study is in the range of 100–200 μm. The component values of the waste powders are listed in Table 2. In the current research, 10%, 20%, 30%, and 40% WGP were prepared to observe the strength effect of WGP on GPC. Tho-In et al. [34] and Jiang et al. [36] expended similar approximate percentages in their works and other mixing percentages remained constant. The mixing percentages of the samples are given in Table 3. Fig. 1 illustrates WGP and fly ash.

Table 2 – Component values of waste powders.

Component	Fly Ash %	WGP %
SiO_2, a	57.3	70–75
Al_2O_3, b	24.9	2.5
Fe_2O_3, c	6.05	0.5
CaO	3.98	7–12
SO_3	0.47	–
Na_2O	1.24	12–15
Cl^-	0.05	–
MgO	–	5
K_2O	–	1.5
Sladge (>45 μm)	17.4	0

40 × 40 × 160 mm prism and 100 × 200 mm cylindrical samples were prepared by compression and curing method, as shown in Fig. 2. A laboratory concrete mixer was preferred to obtain a homogeneous mixture. In the production of GPC samples, steel molds were considered to be heat resistant. Compression and vibration were applied during placing GPC in the molds. It was cured in an oven at 85 °C for 24 h. To analyze the performance of GPC with WGP, three kinds of experiments were carried out. FS tests were performed on the prism samples, and CS and STS tests were conducted on the cylindrical samples. These tests were completed in three replicates for each mix and each test. Prepping of the test samples is presented in Fig. 2. The strength and slump tests were done according to the appropriate standards and are displayed in Fig. 3.

In this study, the effects of slump, penetrability, and setting time were investigated. The mentioned features differ according to the dependent variables. As NaOH molarity increases, the penetrability, settling, and setting times are shortened. It is demonstrated in the results and discussion section of this article that as the WGP content increased, the slump values decreased, and the molarity effect was greater as the setting time increased rather than the increase in the WGP content.

3. Results and discussion

The fundamental purpose of this research was to perform the extensive investigation on numerous production-based subassemblies of cement consumed with definite percentages of fine and coarse aggregates combining with fly ash and WGP. As declared above, to achieve this purpose, percentage of fly ash to WGP was changed as 0%, 10%, 20%, 30% and 40% in the concrete mixture and the effect of molarity of NaOH was also considered. At the end of the analyses, CS, STS, and FS tests were completed. Furthermore, scanning electron microscopy (SEM) analyses were done. Results of the examinations are reported in the following sections.

3.1. *Workability and setting time*

Workability is a significant issue for GPC in terms of the penetrability and durability. The effect of the penetrability was seen in the samples prepping results. The definition of the setting time is expended for the time taken until concrete is

Table 3 – GPC mix materials.

No.	Fly Ash	WGP	WGP/FA	Na_2SiO_3	NaOH	Molarity	Fine Aggregate	Coarse Aggregate
	(kg)	(kg)	%	(kg)	(kg)	M	(kg)	(kg)
1	406.00	0.00	0	145.00	58.00	11	643.00	1194.00
2	365.40	40.60	10	145.00	58.00	11	643.00	1194.00
3	324.80	81.20	20	145.00	58.00	11	643.00	1194.00
4	284.20	121.80	30	145.00	58.00	11	643.00	1194.00
5	243.60	162.40	40	145.00	58.00	11	643.00	1194.00
6	406.00	0.00	0	145.00	58.00	13	643.00	1194.00
7	365.40	40.60	10	145.00	58.00	13	643.00	1194.00
8	324.80	81.20	20	145.00	58.00	13	643.00	1194.00
9	284.20	121.80	30	145.00	58.00	13	643.00	1194.00
10	243.60	162.40	40	145.00	58.00	13	643.00	1194.00
11	406.00	0.00	0	145.00	58.00	16	643.00	1194.00
12	365.40	40.60	10	145.00	58.00	16	643.00	1194.00
13	324.80	81.20	20	145.00	58.00	16	643.00	1194.00
14	284.20	121.80	30	145.00	58.00	16	643.00	1194.00
15	243.60	162.40	40	145.00	58.00	16	643.00	1194.00

produced and compacted, reactions take place, and it gains the early strength. It has been stated that the alkali activator/fly ash and Na_2SiO_3/NaOH have almost no effect on the setting time of GPC, the setting time of GPC depends on NaOH molarity, but the setting time decreases as NaOH molarity increases [51]. In this study, the different molarities of the NaOH dispersion strongly support the setting time in this literature. It was indicated that the use of M11, M13, and M16 NaOH for the reference samples provided the penetrability of approximately 120 min, 100 min, and 15 min, respectively, without sacrificing the strength. With the addition of WGP, the penetrability for M11, M13, and M16 NaOH decreased by an average of 17%, 10%, and 67%, respectively, according to molarity, compared with the M11 reference sample, the penetrability reduced by an average of 17%, 25%, and 95%. In the samples prepared with M16 NaOH, the penetrability became difficult, and the setting time was shortened. Particularly in the samples containing 30% and 40% WGP, the early setting problem occurred until the molds were filled. The results obtained from the reference and WGP added samples are illustrated in Fig. 4. Çelik and Özkılıç [52] obtained a setting time of around 100 min with a concentration of M13 NaOH in their recent GPC study. In this study, a setting time of around 90 min was achieved with M13. The 10-min difference here may be related to WGP consuming more of the solution. Since other parameters were similar, the results confirmed each other. In M11, it was observed that the setting time was extended by 120 min. Jumrat et al. [53] expressed in their similar study that an increase in NaOH molarity reduced the setting time. Therefore, the obtained setting time results seemed consistent. In addition, the Na_2SiO_3/NaOH ratio of 2.5 ensured that the setting time was at appropriate levels. Based on this point, the Na_2SiO_3/NaOH ratio was determined as 2.5 in the study, and its effects on the setting time confirmed the previous studies [54].

3.2. *Slump test*

The slump test was carried out according to the ASTM C143 standard [54]. With the experience from the previous research works and experience gained during this work, the penetrability decreases significantly as temperature and NaOH molarity increase. The slump tests results for NaOH molarity and WGP percentages are depicted in Fig. 5. Three different molarity values and four different WGP contents were tested to ensure the optimum cost and optimum penetrability. The findings revealed that the slump values decreased as molarity increased. On the other hand, the effect of the WGP percentage on the slump was considered by keeping molarity constant. It was detected that the slump values decreased as the



Fig. 1 – WGP and fly ash.



Fig. 2 – Prepping of samples.

WGP percentage increased. It reached nearly zero slump for M16 NaOH content. One of the major problems of GPC is the sufficient slump agglomeration. According to [55], machinability can be enhanced by increasing NaOH or superplasticizer. On the other hand, based on [56], it is possible to increase the slump values in GPC by changing the percentage of Na_2O in Na_2SiO_3. It is clearly seen that the slump values in Fig. 5 decreased very much with the increase in NaOH molarity. The results confirmed the claim of [55]. Since the increase in the WGP ratio used in this study reduced the slump, a small amount of NaOH can be increased depending on increasing the WGP ratio.

3.3. *Detailed examination of CS tests*

The aim of this CS test was to investigate the ability of a sample up to failure under the force. The CS tests on all the concrete samples were conducted in accordance with the ASTM C39 guidelines [57]. For this aim, the dimension of the cylindrical samples test was chosen as 100 mm × 200 mm. In this analysis, the GPC samples were subjected to a longitudinal restraint load at a level of the sample's ruptures. The percentage of NaOH molarity was taken constant as 11 and the percentage of fly ash to WGP was 0%, 10%, 20%, 30%, and 40% in the GPC mixture. In the assessment of the mixture, it was found that as the percentage of fly ash to WGP was changed from 0% to 10%, the change in CS was 23%. When the percentage in the mixture was increased from 0% to 20%, 0% to 30%, and 0% to 40%, CS tend to decrease 40.5%, 56%, and 76%, respectively. Secondly, the value of molarity of NaOH was kept constant as 13 and the percentage of fly ash to WGP was 0%, 10%, 20%, 30%, and 40% in the GPC mixture. In this mixture, as the percentage of fly ash to WGP was changed from 0% to 10%, the change in CS was 23%. When the



Fig. 3 – Performing tests.

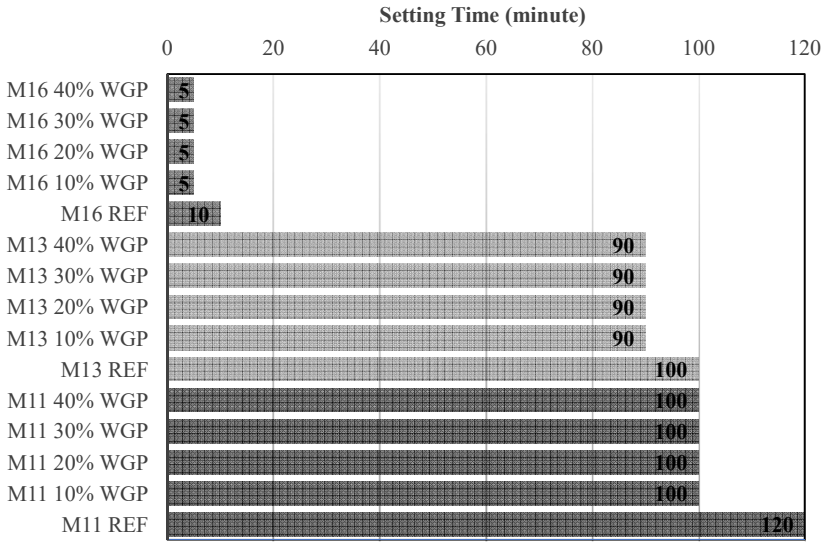


Fig. 4 – Results of setting time.

percentage in the mixture was enhanced from 0% to 20%, 0% to 30%, and 0% to 40%, the rate of change in CS decreased as 9.4%, 19.8%, 43%, and 56%, respectively. Finally, the value of molarity of NaOH was considered constant as 16 and the percentage of fly ash to WGP was 0%, 10%, 20%, 30%, and 40% in the GPC mixture. As the percentage in the mixture was increased, it was noticed that the rate of change in CS reduced as 25%, 40%, 44%, and 51%, respectively. The results of the CS tests are also provided according to the effect of molarity of NaOH in Fig. 6.

Moreover, while the percentage of fly ash to WGP was kept constant, the percentage of NaOH molarity in the mixture was changed as 11, 13, and 16. The percentage of fly ash to WGP was taken as 0%, 10%, 20%, 30%, and 40%, and the percentage of molarity of NaOH was changed as 11, 13, and 16 in the concrete mixture. It was detected that the rate of change in CS increased 8% and 17% for WGP0%, 21% and 15% for WGP10%, 26% and 17% for WGP20%, 19% and 28% for WGP30%, and 34% and 10% for WGP40%. This performance is parallel to that of conventional concrete and is owing to the fact that the optimal percentage of fine to coarse aggregates confirms effective achievement by geopolymer [58]. Additionally, this performance is primarily due to the fact that the NaOH concentration dispersion expended for geopolymer mixture has a constructive impact on dissolution, hydrolysis, and condensation reactions but then condensation of silicate species is inhibited by high alkalinity [59–61]. Consequently, the ideal proportion of fly ash and molarity of NaOH that produced maximal CS for GPC was identified. As shown in Fig. 6, CS enhanced with the increase in NaOH molarity in GPC. However, the quantity of calcium that increased with the increase in WGP further decreased the setting time and penetrability in

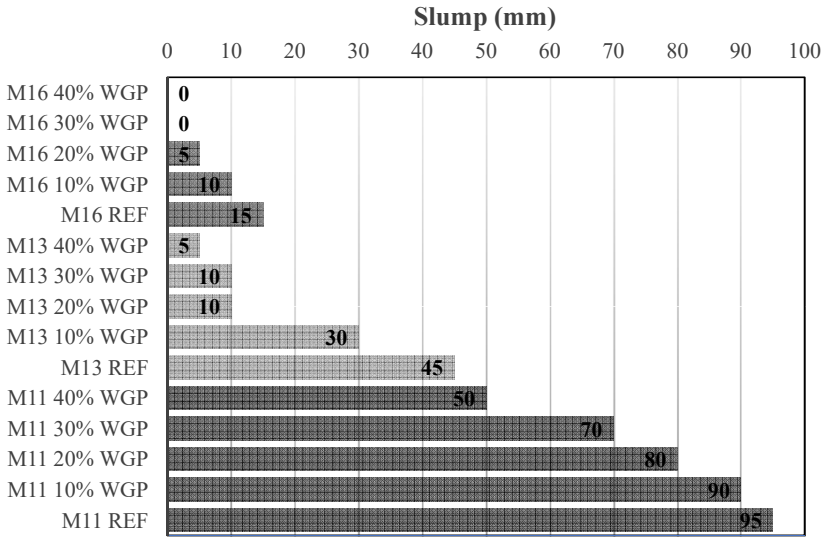


Fig. 5 – Results of slump tests.

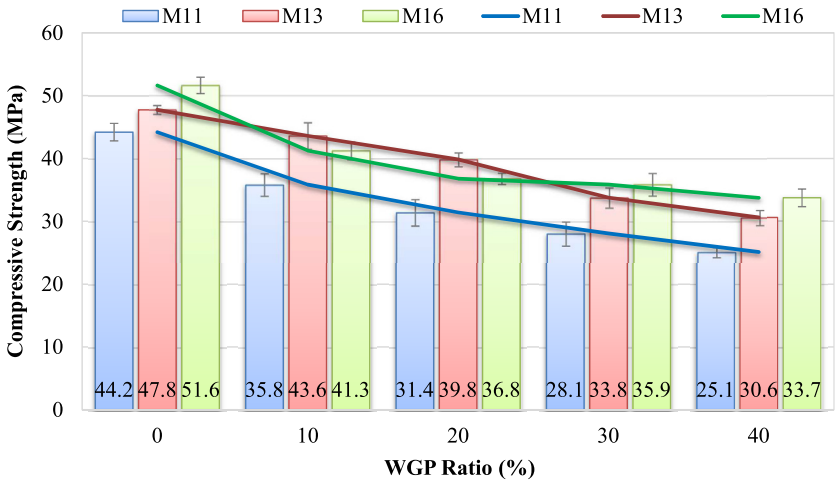


Fig. 6 – Results of CS tests.

GPC and reduced the effect of pozzolan in the mixture. The reduction of the pozzolan effect caused the GPC strength variation. Because of the strong reactive capability of SiO_2 percentage, the geopolymerization's reaction sped up with increasing the WGP levels, which in turn improved the compressive characteristics of the geopolymer binder [62–64]. As the silica/alumina ratio rose, the proportion of WGP used in the matrix decreased, leading to a correspondingly larger fall in the CS properties of the material as an example [34,42,65]. Although M12 was widely expended in the literature, the use of M13 in the GPC application with WGP resulted in good strength, and there were no problems in the prepping phase. The CS results of GPC with added WGP demonstrated similar behavior with similar studies in the literature. Derinpinar et al. [32] determined that CS of the GPC samples cured at high temperatures decreased because of the increased WGP ratio. Sethi et al. [37] found that with the addition of WGP and GGBS, CS decreased with increasing M4, M8, and M12 NaOH, but with 10% GGBS and 20% WGP, a higher result was obtained with M12. The calcium ratio in GGBS used here may have given a positive result on CS. Deb et al. [66] and Duxon et al. [67] argued that the increased GGBS was mainly responsible for the early strength gain of GPC, while WGP was responsible for the strength gain at later ages. Vafaei and Allahverdi [68] studied that by increasing NaO_2 with the increase in WGP addition, the enhancement in CS was obtained for geopolymer mortars. When the graphs in Fig. 6 are carefully examined, it is seen that 10% WGP and M13 NaOH can be expressed as the optimum values.

3.4. *Detailed examination of STS tests*

As illustrated in Fig. 7, the STS results regularly follow the parallel trend as those of CS. The value of molarity of NaOH was considered as M11 and the percentage of fly ash to WGP was taken as 0%, 10%, 20%, 30%, and 40% in the concrete mixture. In the assessment of the mixture in which the percentage of fly ash to WGP altered from 0% to 10%, the change in STS was found as 2.8%. When the percentage in the mixture was increased to 20%, 30%, and 40%, STS decreased to 15.5%, 35%, and 64%, respectively. Next, the value of molarity of NaOH was kept constant as M13 and the percentage of fly ash to WGP was 0%, 10%, 20%, 30%, and 40% in the concrete mixture. As the percentage of fly ash to WGP was increased from 0% to 10%, the rate of change in CS was found 4.5%. While the percentage in the mixture was improved to 20%, 30%, and 40%, it was discovered that this rate of change tended to decrease as 14%, 47.3%, and 77.6%, respectively. Finally, the value of molarity of NaOH was considered constant as 16 and the percentage of fly ash to WGP was altered as 0%, 10%, 20%, 30%, and 40% in the concrete mixture which resulted in STS decreases of 32%, 50%, 61%, and 66%, respectively.

In these tests, the percentage of fly ash to WGP was constant and the percentage of molarity of NaOH was altered to M11, M13, and M16. Also, the percentage of fly ash to WGP was 0%, 10%, 20%, 30%, and 40%, while the percentage of molarity of NaOH was changed as M11, M13, and M16. It was concluded that STS decreased as 16% and 36% for WGP0%, 14% and 6% for WGP10%, 17% and 4% for WGP20%, 6.4% and 14% for WGP30%, and 7% and 34% for WGP40%. The results of the STS tests are depicted in Fig. 7 according to the effects of molarity of NaOH and WGP ratios. In Fig. 8, the STS versus CS tests results are represented. WGP's filling ability and pozzolanic character, which enhance the interfacial transition zone between the binder and aggregates, are credited with improving the material's STS [42,69]. The brittle characteristics of WGP indicated to reduce STS for greater WGP replacement levels in the ternary combination [42,63]. Another similar study found that excessive addition of WGP reduces STS of GPC. Sethi et al. [37] revealed that STS of GPC decreased as the WGP substitution ratio increased in GPC. Derinpinar et al. [32] reported that this is due to the slow formation of the pozzolanic reaction of WGP and the characteristic of the interfacial transition zone. On the other hand, Li et al. [70] believed that the STS/CS ratios of the GPC samples decreased due to the temperature increase, which were between 10.1% and 10.9%. Albidah et al. [71] reported that it was between 10.1% and 13.6%. Thus, it can be concluded that the results obtained from the literature generally support the results of GPC with added WGP.

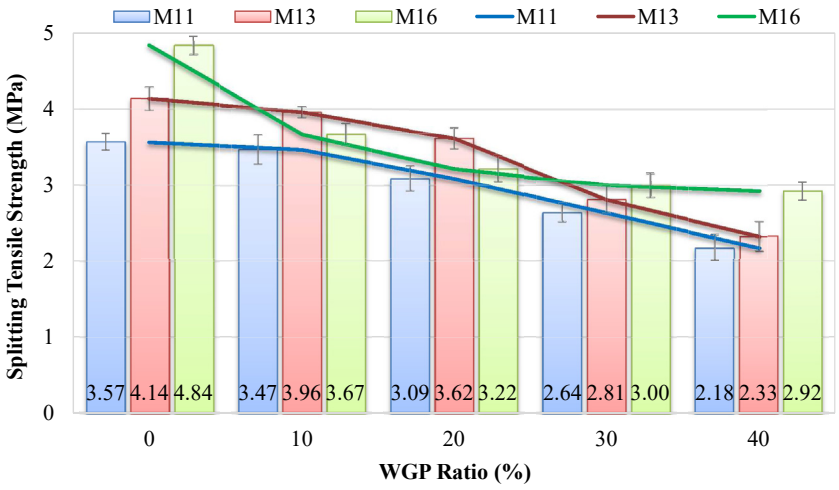


Fig. 7 – Results of STS tests.

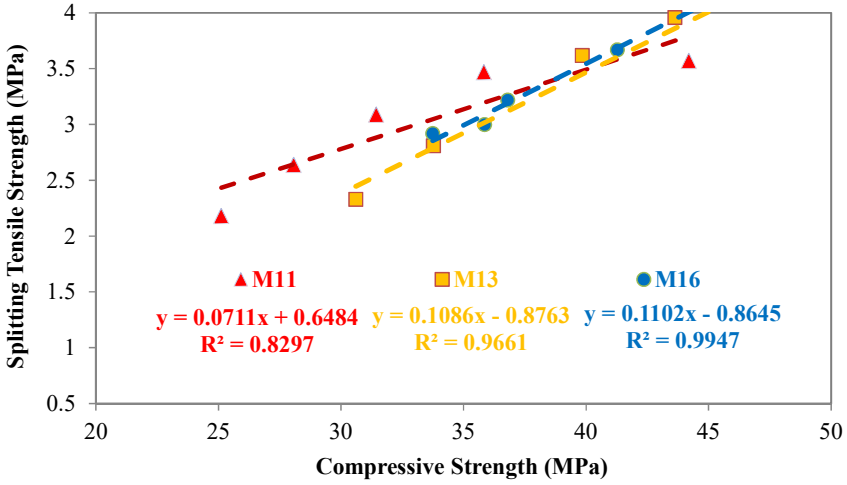


Fig. 8 – STS vs. CS tests results.

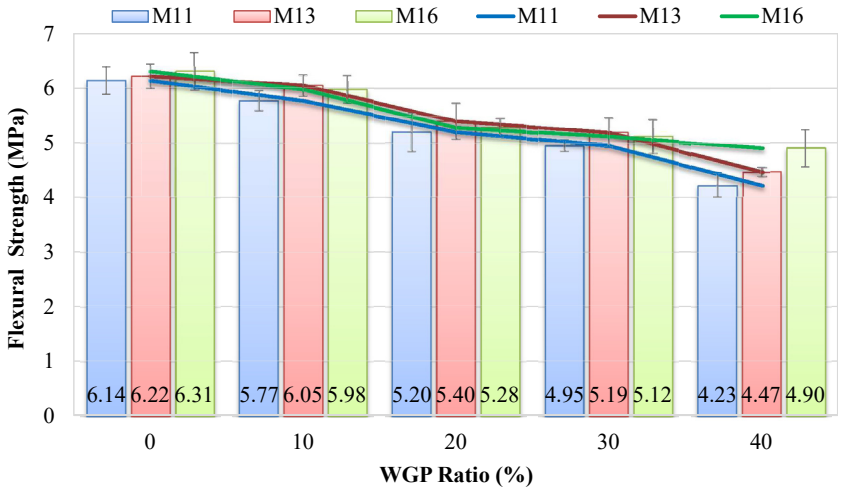


Fig. 9 – Results of FS tests.

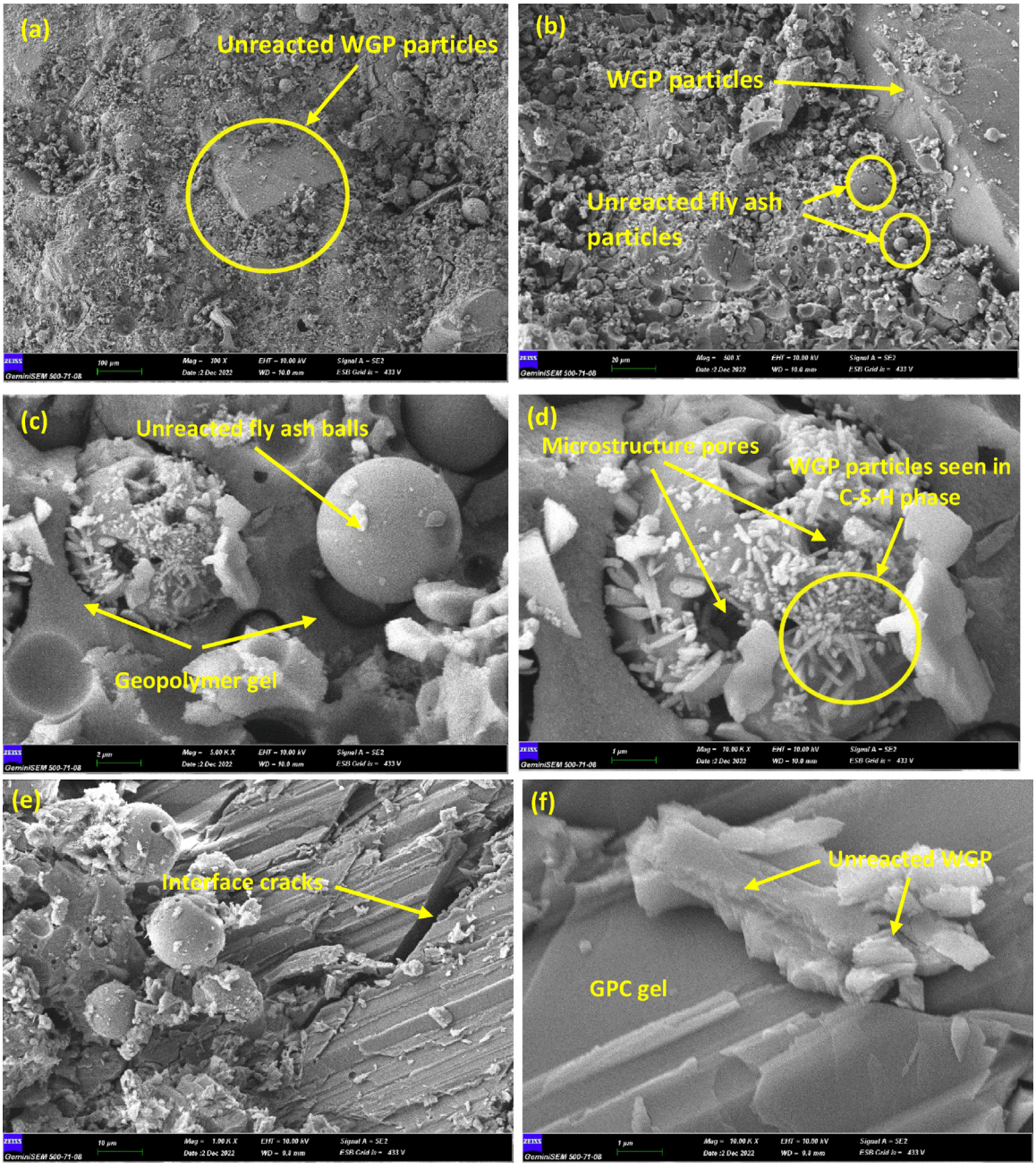


Fig. 10 – SEM micrographs.

3.5. *Detailed examination of FS*

The capacity of the samples exposed to the flexure can be taken as the tensile strength of GPC. On the other hand, FS is commonly greater than the indirect STS [63,64]. FS of the samples was evaluated. The value of molarity of NaOH was M11 and the percentage of fly ash to WGP was 0%, 10%, 20%, 30%, and 40% in the GPC mixture. When the percentage of fly ash to WGP changed from 0% to 10%, the rate of change in FS was established as 6.4%. However, when the percentage of fly ash to WGP changed from 10% to 20%, 20%-to 30%, and 30%-to 40%, it was noticed that FS decreased 18%, 24%, and 45%, respectively. Following that, the value of molarity of NaOH was chosen constant as M13 and the percentage of fly ash to WGP was 0%, 10%, 20%, 30%, and 40% in the GPC mixture. While the percentage in the mixture was enhanced from 0%, to 10%, 20%, 30% and 40%, it was found that FS reduced 2.8%, 15%, 19.8%, and 39%, respectively. As the final stage, the value of molarity of NaOH was employed constant as 16 and the percentage of fly ash to WGP was improved from 0%, to 10%, 20%, 30%, and 40% in the concrete mixture. In this case, it was observed that FS decreased 5.5%, 19.5%, 23%, and 29%, respectively. In addition, it was noticed that the rate of variation in FS tended to increase as 1.3% and 2.7% for WGP0%, 4.8% and 3.6% for WGP10%, 3.8% and 1.5% for WGP20%, 4.8% and 3.4% for WGP30%, and 5.6% and 15.8% for WGP40%. The

results of the FS tests are depicted in Fig. 9 in accordance with the effect of molarity of NaOH and WGP ratios. Due of the less reactive parent materials included in WGP, increasing the replacement percentages of WGP has a detrimental effect on FS [42,72,73]. Some researchers have stated that factors such as FS of WGP added GPC, the composition of GPC, the type and ratio of WGP, and the process parameters may be effective. For example, Phoo-ngernkham et al. [74] mentioned that FS may increase during gel reactions such as C-S-H. According to Kumar et al. [75], the ductility of GPC increased with the addition of WGP. On the other hand, Uysal et al. [76] uncovered that FS of the waste added GPC samples was adversely affected in general. When Fig. 9 is evaluated, it is clear that there has been a decrease in FS with increasing WGP. However, it is seen that 10% WGP performed better with M13 NaOH than other M11 and M16.

3.6. *Microstructural assessment*

After CS and FS tests, the GPC samples manufactured using WGP were subjected to the SEM assessment. The SEM analysis was done to show the micro-level structure of GPC and WGP. When the microstructures of both GPC and WGP were assessed, glassy structures and sharp-edged irregular formations drew attention. GPC particles had sharper edges and forms, but WGP particles had smoother surfaces, sharper prismatic edges, and a greater density [1,31]. Vafai and Allaverdi [68] obtained a similar result from the SEM analysis, as illustrated in Fig. 10(a). The image in Fig. 10(b) is a double magnification of the image in Fig. 10(a). A close look at Fig. 10(b) displays unreacted particles (WGP and fly ash) [29]. Besides, unreacted fly ash and WGP particles are seen in Fig. 10(c) [36]. Similar results were found by Jiang et al. [36]. Fig. 10(d) indicates both voids and calcium silicate hydrate (C–S–H) together. Similar results were obtained in another study by Celik and Özkılıç [52]. Interface cracks are visible in Fig. 10(e). In a similar study, Jiang et al. [36] reported the same. Fig. 10(f) demonstrates more clearly unreacted WGP and GPC gel. When SEM images were assessed, it was observed that WGP provided good binding with fly ash in general. Although the microcracks were witnessed in some regions, a good microstructure was seen.

4. Conclusions

In this study, the effect of WGP with fly ash in certain proportions on GPC was examined by exchanging different proportions of molarity and WGP percentages in GPC. Therefore, the molarity values of the NaOH dispersion considered in the study were as M11, M13, and M16. Furthermore, the percentage of fly ash to WGP was changed as 0%, 10%, 20%, 30%, and 40% in the concrete mixture. In the hardened condition, CS, STS, and FS of the samples were detected. Additionally, SEM investigation was also taken into account to compare the strength implications gained from the study. The following conclusions can be drawn from this research.

- It was found that with the addition of WGP, the workability for M11, M13, and M16 NaOH reduced by an average of 17%, 10%, and 67%, respectively.
- The results revealed that the slump values reduced as molarity enhanced. In addition, the effect of WGP percentage on the slump was examined by keeping molarity constant. It was detected that the slump values reduced as the WGP percentage increased.
- The value of NaOH was M11, M13, and M16 and the percentage of fly ash to WGP was changed as 0%, 10%, 20%, 30%, and 40% in the GPC mixture. At the end of these analyses, it was found that while percentage of fly ash to WGP in the mixture was increased, a decrease in CS was observed. This decreasing rate was seen as 23%, 40.5%, 56%, and 76% for M11, 9.4%, 19.8%, 43%, and 56% for M13, and 25%, 40%, 44%, and 51% for M16. Moreover, an increase in CS was detected when molarity was changed from M11 to M13 and M13 to M16. It was witnessed that it increased 8% and 17% for WGP0%, 21% and 15% for WGP10%, 26% and 17% for WGP20%, 19% and 28% for WGP30%, and 34% and 10% for WGP40%.
- The outcomes of STS commonly followed the similar trend as those of CS. While percentage of fly ash to WGP in the mixture was increased, a decrease in the results was achieved. This decreasing rate was 2.8%, 15.5%, 35%, and 64% for M11, 4.5%, 14%, 47.3%, and 77.6% for M13, and 32%, 50%, 61%, and 66% for M13. Furthermore, an increase in STS was obtained when molarity was changed from M11 to M13 and M13 to M16. It was found that it enhanced as 16% and 36% for WGP0%, 14% and 6% for WGP10%, 17% and 4% for WGP20%, 6.4% and 14% for WGP30%, and 7% and 34% for WGP40%.
- However, when the percentage of NaOH was taken as 0%, 10%, 20%, 30%, and 40%, the percentage of fly ash to WGP was increased in the concrete mixture. It was uncovered that while the percentage of fly ash to WGP was increased in the concrete mixture, a decrease in the results was seen.
- Regarding FS of the tested samples, while the proportion of fly ash to WGP was kept constant and the rate of molarity of NaOH proportion was altered from M11 to M13 and M13 to M16, it was observed that the amount of increase in the results was 1.3% and 2.7% for WGP0%, 4.8% and 3.6% for WGP10%, 3.8% and 1.5% for WGP20%, 4.8% and 3.4% for WGP30%, and 5.6% and 15.8% for WGP40%.
- In the SEM assessments, while the microstructures of both GPC and WGP were detected, glassy structures and sharp-edged asymmetrical constructions attracted the attention. The GPC subdivisions had sharper edges and forms, but the WGP subdivisions seemed to have smoother surfaces, sharper prismatic edges, and more density.
- Utilizing 10% WGP and NaOH molarity of 13 is recommended to obtain the optimum setting time, workability, and strength for sustainable GPC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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