Fresh and mechanical properties overview of alkali-activated materials made with glass powder as precursor

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Cleaner Materials 3 (2022) 100036

Contents lists available at ScienceDirect

Cleaner Materials

journal homepage: www.elsevier.com/locate/clema

Fresh and mechanical properties overview of alkali-activated materials made with glass powder as precursor

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ARTICLE INFO

Keywords:
Alkali-activated materials
Glass powder
Precursor
Activators

ABSTRACT

Alkali-activated materials (AAMs) are promising materials that can be used as alternatives for conventional Portland cement (PC) materials. In this paper, the fresh properties, and mechanical properties of AAMs made with glass powder (GP) as the precursor were explored and discussed. The discussions presented in this paper showed that the incorporation of GP as the precursor in AAMs resulted in an improvement in the workability and extension of the set times. However, the use of GP especially at early ages could result in a detrimental impact on the mechanical performance of AAMs due to the lower reactivity of GP compared to other precursors. Nonetheless, AAMs with acceptable mechanical performance for non-structural and structural applications can still be produced with the use of GP as the precursor.

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Abbreviations: AAM(s), alkali-activated material(s); FA, fly ash; GP, glass powder; MK, metakaolin; PC, Portland cement; SC, sodium carbonate; SH, sodium hydroxide; SL, slag; SS, sodium silicate.

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https://doi.org/10.1016/j.clema.2021.100036
Received 27 October 2021; Revised 23 November 2021; Accepted 13 December 2021

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1. Introduction

The advent of alkali-activated materials (AAMs) as a sustainable alternative for the Portland cement (PC) materials have led to the use of various materials as aluminosilicate precursor in the production of AAMs (Dhasindrakrishna et al., 2021; Giogetti et al., 2021; Provis, 2018; Shi et al., 2019). The conventional precursors used in AAMs are fly ash (FA) and slag (SL) (Gülşan et al., 2019; Prusty and Pradhan, 2020; Zakka et al., 2021; Zhang et al., 2020b). However, these materials are not available locally in various parts of the world and their sourcing from external regions could eliminate the sustainability benefits associated with the use of AAMs in place of PC materials. For example, the increasing environmental awareness in places such as Canada has resulted in the decommissioning of coal power plants; consequentially limiting the supply of FA available to produce AAMs. It is worth mentioning that these conventional precursors (i.e. FA and SL) are also extensively used as partial replacement of PC in various construction applications (Joshaghani et al., 2018; Kou et al., 2011; Teh et al., 2017). Thus, it is critical to seek other alternative sources of precursors that can be used in the production of AAMs. Some of the promising and effective sources of precursors are waste materials generated from various industrial processes. The ability to process various waste materials and use them as a precursor in AAMs would not only supplement the need for precursors but also open an efficient pathway to manage these wastes.

Of such waste material that can be used as an alternative for the conventional precursors in AAMs is glass powder (GP) (Lv et al., 2019; Maraghechi et al., 2017; Pourabbas Bilondi et al., 2018). GP is obtained from processing glass wastes. The United States Environmental Protection Agency has estimated that over 10 million tons of glass were generated as waste in the United States alone annually (Environmental Protection Agency Office of Resource Conservation, 2013). Due to the different colours of glass products and the presence of impurities, it has been estimated that less than 10% of these wastes are recycled for the production of new glass products (Jani and Hogland, 2014; Ling et al., 2013). With the similar high generation of these glass wastes in other countries, an effective way to manage these wastes must be sought for and put in place. The conventional method of managing glass wastes is by disposal in landfills (Mohajerani et al., 2017). However, this method entails the use of valuable land spaces to store these wastes. The high use of glass products due to the rapid global urbanization and increase in population is expected to result in more generation of glass wastes in the coming years. Thus, finding an alternative way to process these glass wastes and reuse them for construction applications would result in a significant reduction in the need to use valuable land spaces for landfilling.

Various studies have utilized glass wastes as aggregates in various construction materials such as cementitious materials (Adesina and Das, 2020a; Omoding et al., 2021). However, these glass wastes can be further processed and used as the binder composition in cementitious materials. Extensive studies have shown that GP can be used to partially replace Portland cement in cementitious materials (Adesina and Das, 2020b; Jiang et al., 2019; Shoaei et al., 2020). However, GP can also be used as a precursor in AAMs. In addition to the benefit of using GP as a precursor in AAMs, it also supplements the current high demand for various raw materials used in the production of construction materials. As GP is also obtained from glass wastes, they can be deemed more economical compared to when conventional raw materials such as PC are used in construction applications (Rivera et al., 2018; Xiao et al., 2020a). Studies have shown that the use of GP in construction materials such as cementitious materials would result in a significant reduction in the embodied energy and cost of the materials (Bheel and Adesina, 2020; Tho-In et al., 2016). Due to the high silica content in GP, it can be utilized as a precursor in the synthesis of AAMs. However, compared to the conventional precursors such as fly ash (FA) and slag (SL); there are limited studies and uses of GP in AAMs.

With limited studies on the use of GP in AAMs, this comprehensive review was carried out to explore the influence of GP on the fresh and mechanical properties of AAMs based on the existing studies. The fresh properties evaluated in this review are setting time and workability while the mechanical properties cover the compressive strength, bond strength, flexural strength and split tensile strength. Some applications of GP-based AAMs were also discussed, and recommendations were provided for future studies. It is anticipated that the discussion presented in this paper would be a good resource for stakeholders interested in the use of alternative precursors in AAMs. It is also hoped that the information in this review paper would propel more research, development, and applications of GP in AAMs.

2. Glass powder

GP is processed from various glass wastes by crushing/milling as shown in Fig. 1 to obtain fine particles (i.e. GP) that can be used as a precursor in AAMs. Some common sources of the glass wastes used in the production of GP are presented in Table 1. It is worth mentioning that the source of the glass wastes would have an influence on the chemical composition of the resulting GP and the corresponding performance. However, numerous studies on the use of GP in AAMs and PC materials have indicated that GP is mostly composed of primarily silicate, sodium and calcium which made up about 90% of its chemical composition (Adesina and Das, 2021; Cercel et al., 2021; He et al., 2020; Sevinç and Durgun, 2020). The morphology of GP is irregular and flaky compared to that of precursors such as FA which is spherical (Jiang et al., 2020; Liang et al., 2021; Zhang et al., 2020b).

3. Properties of AAMs incorporating GP as a precursor

3.1. Workability

Si et al. (2020b) evaluated the workability of AAMs made with GP as partial replacement of MK up to 20% using the mini-slump test (ASTM, 2013). The findings from the study showed that the workability of the fresh AAMs increased with higher content of GP as shown in Fig. 2. The enhancement in the workability of the AAMs with the incorporation and higher content of GP can be ascribed to the physical properties of the GP. GP possesses a lower surface area and large particle size compared to that of MK thereby reducing the demand for the liquid to wet the precursor and more water available for the workability of the mixture (Pacheco-Torgal et al., 2011; Quercia et al., 2012; Si et al., 2020b). These observations are in agreement with that of Lu and Poon (2018) where an increase in workability was observed when GP

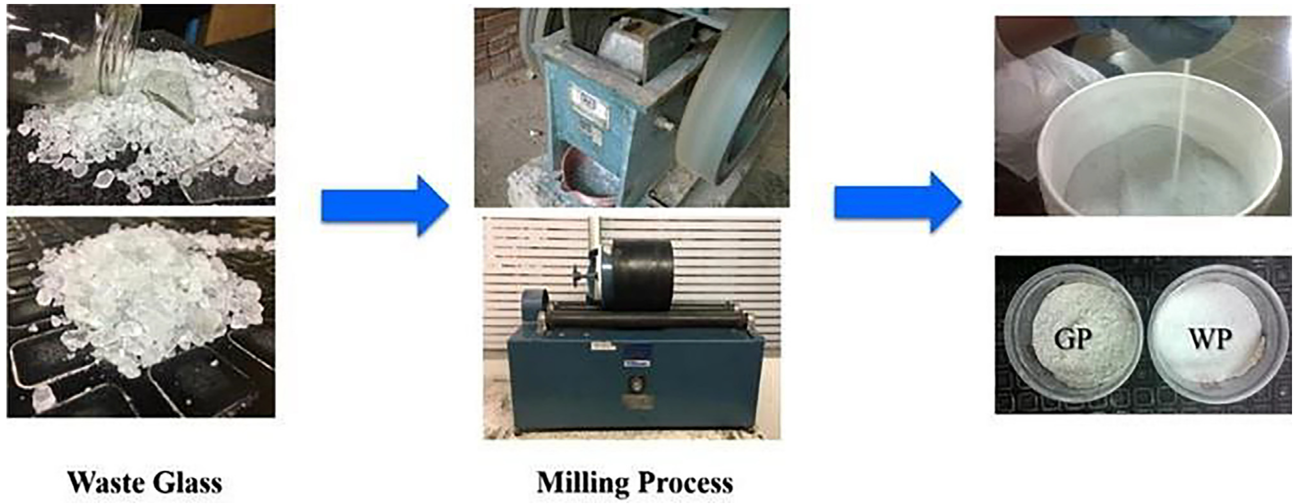

Fig. 1. Processing of glass wastes to GP (reused with permission (Rivera et al., 2018)).

Table 1
Source and primary composition of GP used in AAMs.

Source	SiO_2	Na_2O	CaO	Reference
Fluorescent lamps	58.4	15.3	11.7	(Bobirică et al., 2015)
Glass containers	68.8	15.2	7.43	(Tho-In et al., 2016)
Solar panel	72.3	12.9	8.98	(Hao et al., 2013)
Highway safety glass	72.5	13.7	9.70	(Redden and Neithalath, 2014)
Glass bottles	72.6	12.5	10.5	(Xiao et al., 2020b)

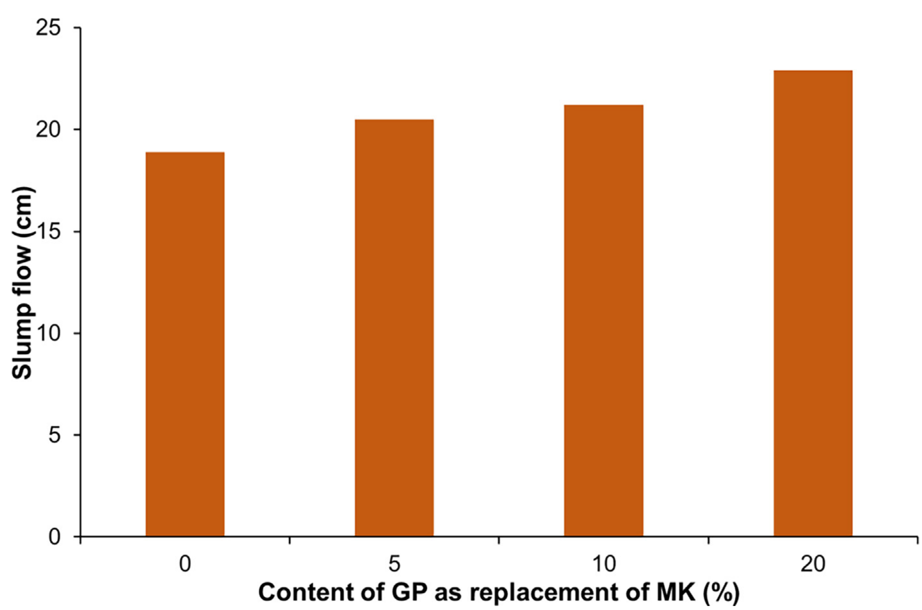

Fig. 2. Influence of GP content on workability (adapted from (Si et al., 2020b)).

was used to replace 30% FA and SL in AAMs. A similar observation was also reported by Dadsetan et al. (2021) where an extensive evaluation of the effect of GP on the rheology of MK-based AAMs was carried out.

In another study, Jiang et al. (2020) utilized GP as up to 30% replacement of FA in AAMs. The findings from the study also indicate an increase in the workability of the fresh AAMs with higher GP content. The use of GP as 10%, 20% and 30% replacement of the FA resulted in an increase in the flow by 3%, 11% and 14%, respectively when compared to AAM made with only FA as the precursor. The increase in the flow of the fresh AAMs when GP was incorporated was attributed to the smooth surface of GP which embodied it with lower water absorption. The presence of fewer clusters in the AAMs due to the presence of GP was also linked to the increase in flow (Vafaei and Allahverdi, 2017). These results are in agreement with that of Samarakoon et al. (2020) where up to 80% improvement in the workability of the AAMs was achieved when GP was used to replace up to 30% FA as the precursor.

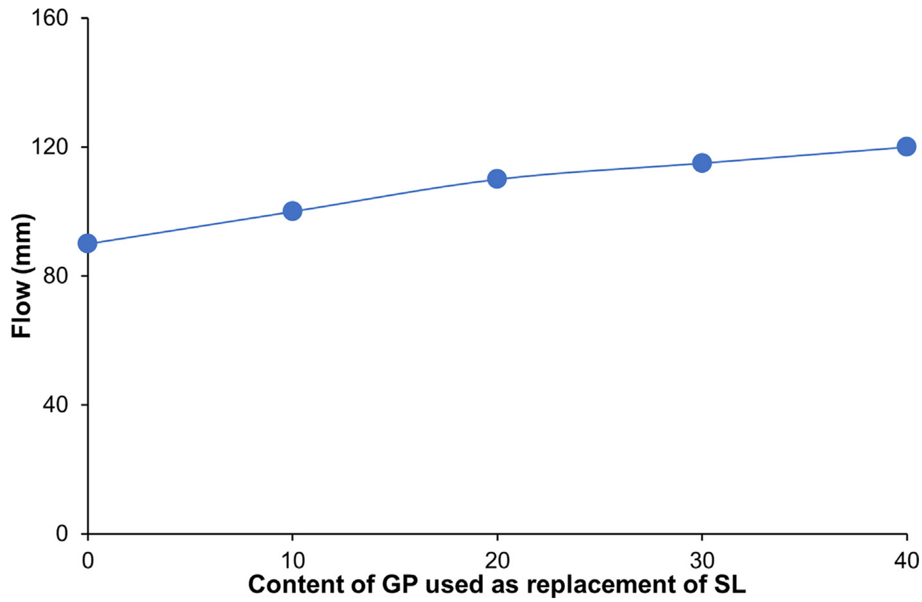

Fig. 3. Influence of GP content on workability (adapted from (Shoaei et al., 2020)).

Similar observation as shown in Fig. 3 has also been reported by Shoaei et al. (2020) where GP was used as up to 40% replacement of SL as a precursor in AAMs. The use of GP to replace 10%, 20%, 30% and 40% of SL resulted in an increase in the flow by 11%, 22%, 28% and 33%, respectively when compared to the AAM made with only SL as the precursor. These findings are also consistent with that of Liu et al. (2019a) where the use of GP to replace 40% of either FA or SL resulted in an improvement in the workability. Liang et al. (2021) also reported an increase in the workability of AAMs by 11.4%, 27.3%, 46.9% when GP was used to replace MK by 10%, 20% and 30%, respectively.

3.2. Setting time

Results from the setting times assessment carried out by Si et al. (2020b) using the Vicat needle method (ASTM, 2008) are presented in Fig. 4. It is evident from Fig. 4 that the setting times of the AAMs were extended with the presence and higher content of GP used as the partial replacement of MK as the precursor. The extension in the setting time due to the incorporation of GP was attributed to the reduction in the reaction rate resulting in a lower polycondensation rate and slower formation of activation products (Novais et al., 2016). This observation is consistent with that of Liang et al. (2021) where GP was used to replace MK up to 30%. A similar observation has been reported by Samarakoon et al. (2020) where the incorporation of GP as replacement of up to 30% FA as a precursor resulted in an increase in both the initial and final set times. However, the increase in the setting time due to the incorporation of GP was linked to the physical properties of the GP which resulted in more additional water available in the fresh AAM (Lu et al., 2017). Huseien et al. (2020) also reported an extension in the set times when nano GP was used as up to 20% replacement of the SL in AAMs.

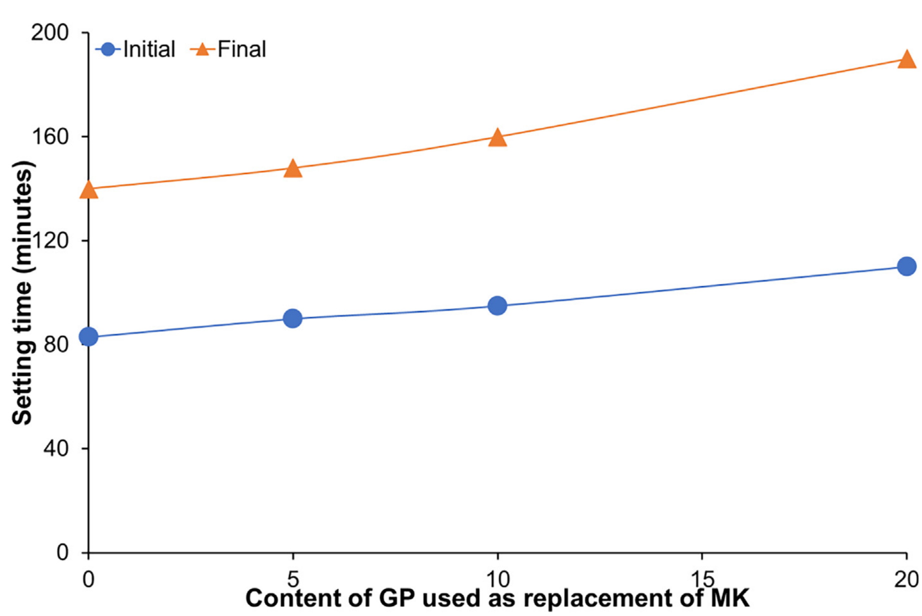

Fig. 4. Influence of GP content on setting time (adapted from (Si et al., 2020b)).

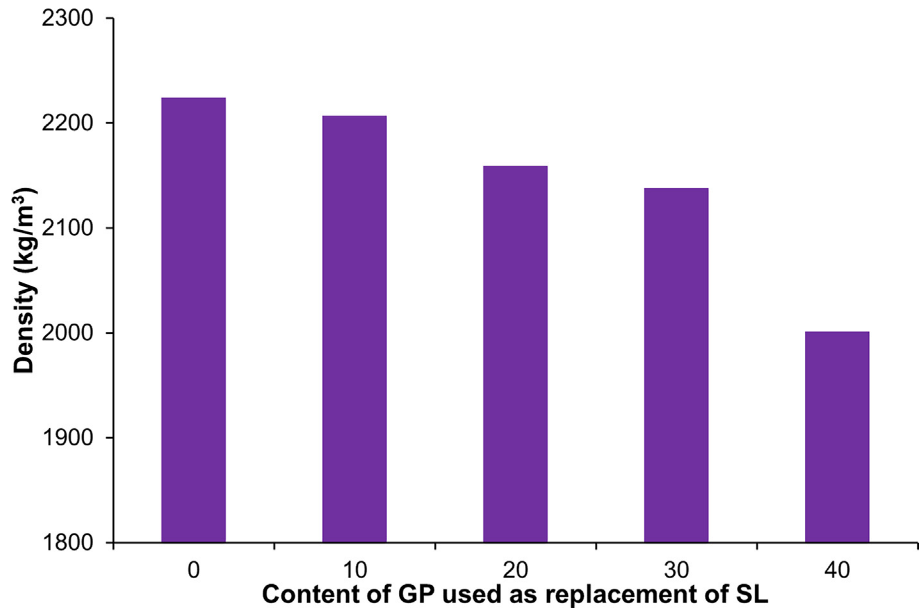

Fig. 5. Influence of GP content on density (adapted from (Shoaei et al., 2020)).

In contrast, the study by Jiang et al. (2020) where GP was used as the replacement of up to 30% FA indicated a decrease in the final setting time of the AAMs. The replacement of FA with 10%, 20% and 30% GP as precursor resulted in 6.8%, 21.9%, and 26.6%, respectively reduction in the final setting time when compared to that of AAM made with only FA as the precursor. The decrease in the set time with the incorporation of GP was linked to the presence of more reactive silica in the GP resulting in the faster formation of three-dimensional aluminosilicate structures. Similar findings have been reported by Liu et al. (2019a) where the use of GP to replace 40% of FA in SH and SC activated AAMs resulted in a decrease in the set times. However, similar to AAMs made with other types of precursors, the setting times of AAMs incorporating GP can be accelerated with the use of heat curing for the first 24 h after casting (Si et al., 2020a).

3.3. Density

The use of GP as a precursor in AAMs has been found to result in a reduction in density. The study by Shoaei et al. (2020) showed that the use of GP as up to 40% replacement of SL as precursor resulted in up to 10% reduction in the density as shown in Fig. 5. The reduction in the density of the AAMs when GP is utilized can be linked to the lower specific gravity of GP compared to other precursors such as SL. In contrast, the study by Liang et al. (2021) showed that the densities of AAMs incorporating GP as 10% and 20% replacement of MK is higher compared to those without GP. However, when the content of GP was increased to 30%, there was a decrease in the density of the AAMs. The higher density of AAMs made with GP as 10% and 20% replacement of the MK was linked to the formation of additional reaction products resulting in the densification of the microstructure.

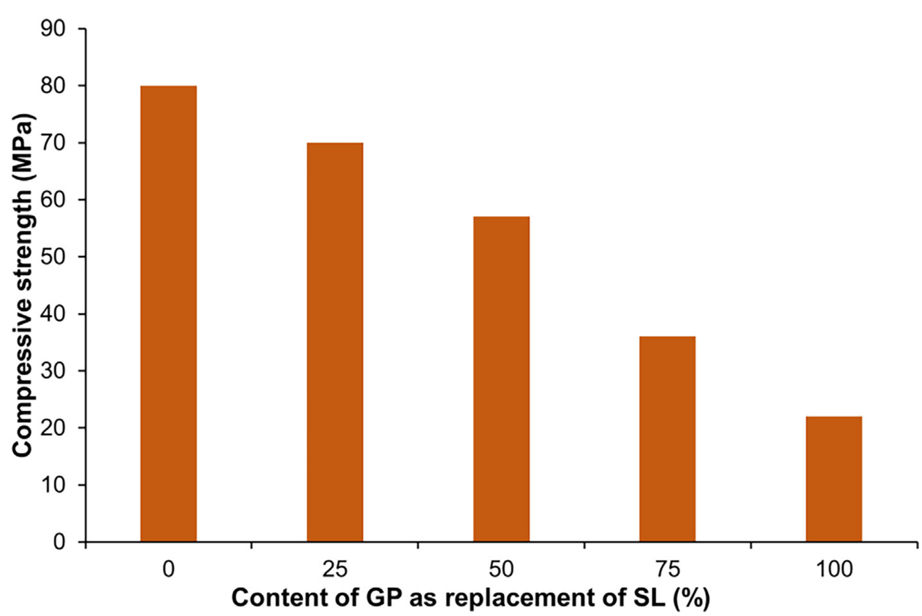

Fig. 6. Influence of GP content on compressive strength (adapted from (Zhang et al., 2020a; Zhang et al., 2020b)).

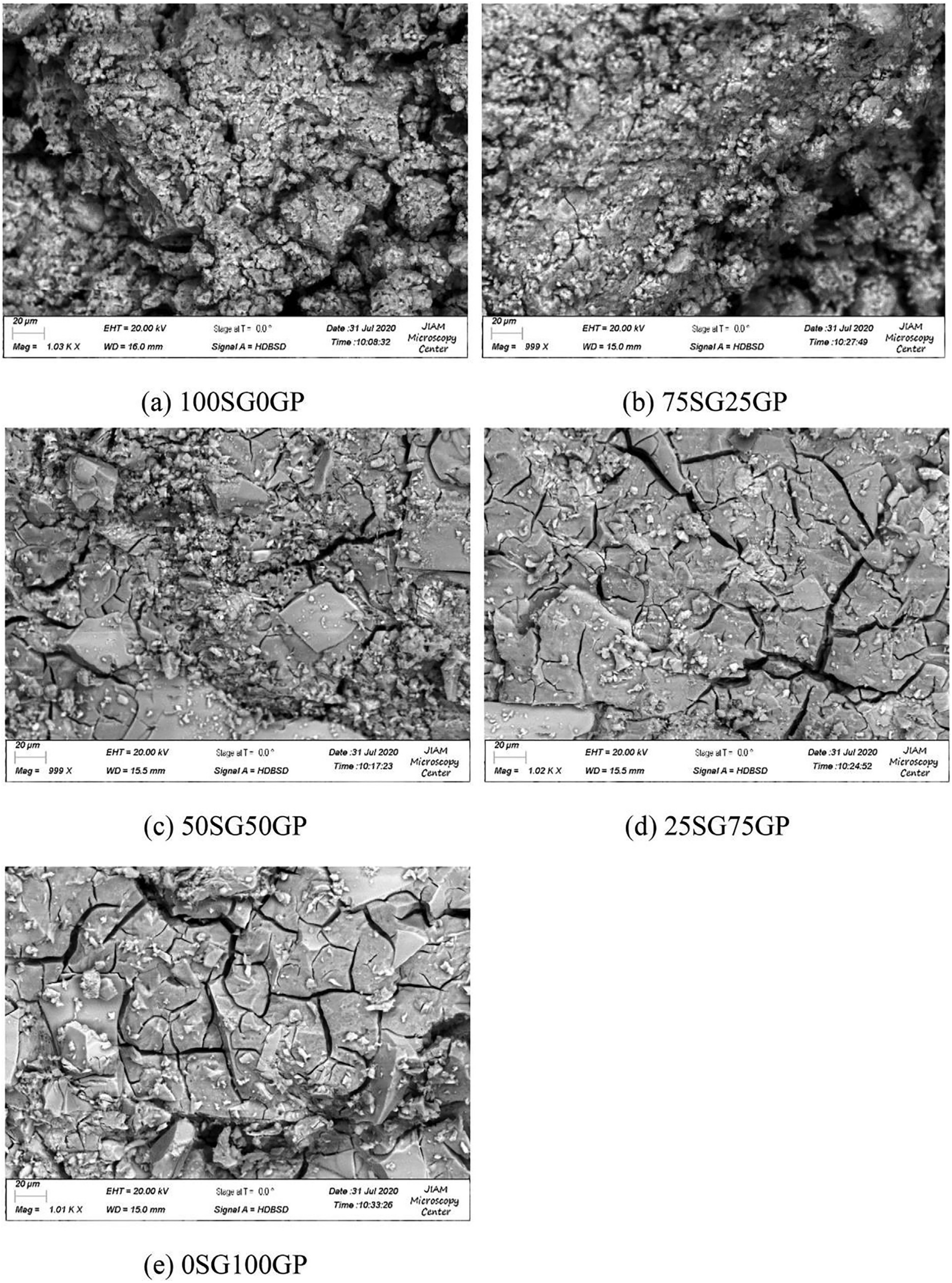

Fig. 7. SEM image of AAMs produced with GP as precursor (reused with permission (Xiao et al., 2021)).

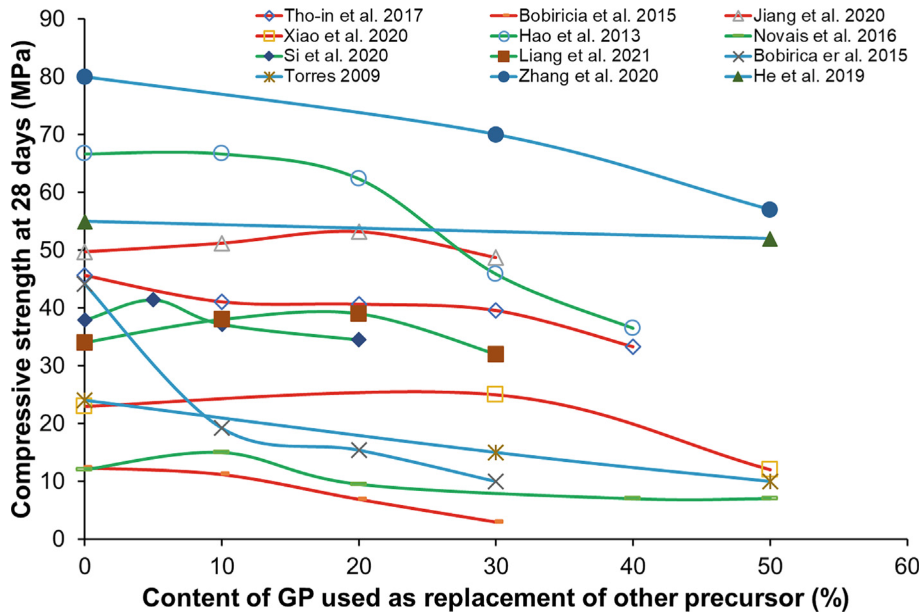

Fig. 8. Influence of GP content on the compressive strength of AAMs made with other precursors.

3.4. Compressive strength

The use of GP as a replacement of SL up to 100% has been found to result in a reduction in the compressive strength of AAMs regardless of the activator type (Torres et al., 2009). This observation is consistent with that of Zhang et al. (2020a) and Zhang et al. (2020b) where the use of GP as a partial and total replacement of SL as a precursor was found to yield lower strength as shown in Fig. 6. The reduction in the compressive strength of the AAMs with higher content of GP was linked to the lower reactivity of GP compared to that of SL. Similarly, the study by Tho-In et al. (2016) showed that the incorporation of two types of GP as partial replacement of FA as precursor resulted in a reduction in compressive strength. The compressive strength of AAM made with GP as 10%, 20%, 30% and 40% replacement of FA as the precursor is 10.1%, 10.9%, 13.3% and 27.1%, respectively lower than that of the control AAM with only FA as the precursor. The reduction in the compressive strength was ascribed to the increase in the silicate to aluminate ratio resulting in the formation of low-crosslinked products.

These results are in agreement with that of Xiao et al. (2020a) where the use of GP to replace FA up to 100% was found to result in a reduction in the compressive strength. The use of GP to replace SL up to 100% was also found to yield lower compressive strength (Xiao et al., 2021). The reduction in the compressive strength when GP was incorporated was linked to the lower reactivity of GP compared to SL resulting in a lower product formation and a more porous structure. The microstructural investigations carried out by Xiao et al. (2021) indicate the microstructure of the AAMs becomes more porous with higher content of GP as shown in Fig. 7. A similar observation was reported by Bobirică et al., 2015 where the increase in the Si/Al ratio due to the incorporation of GP as a precursor in FA and SL-based AAMs resulted in a decrease in the compressive strength. A

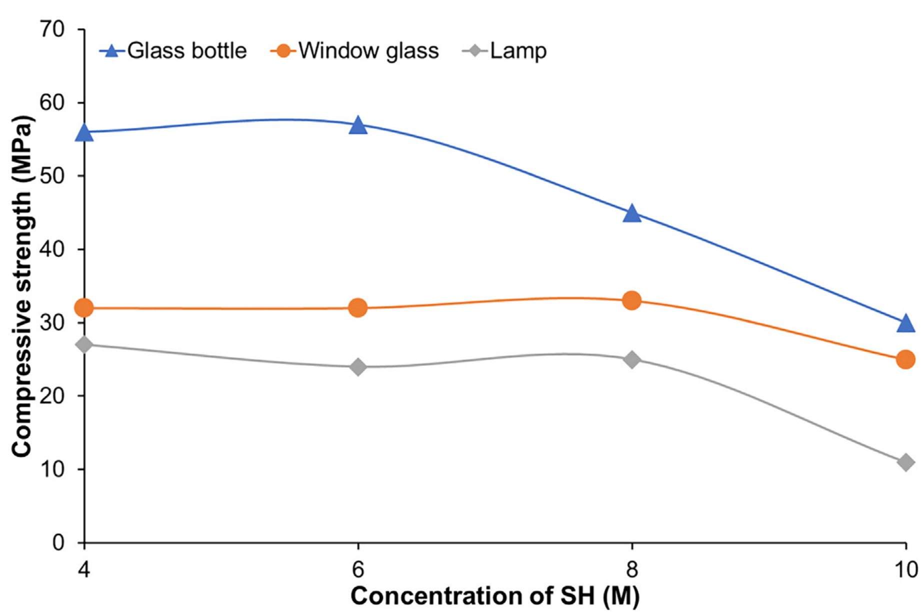

Fig. 9. Influence of GP source and SH concentration (adapted from (Rivera et al., 2018)).

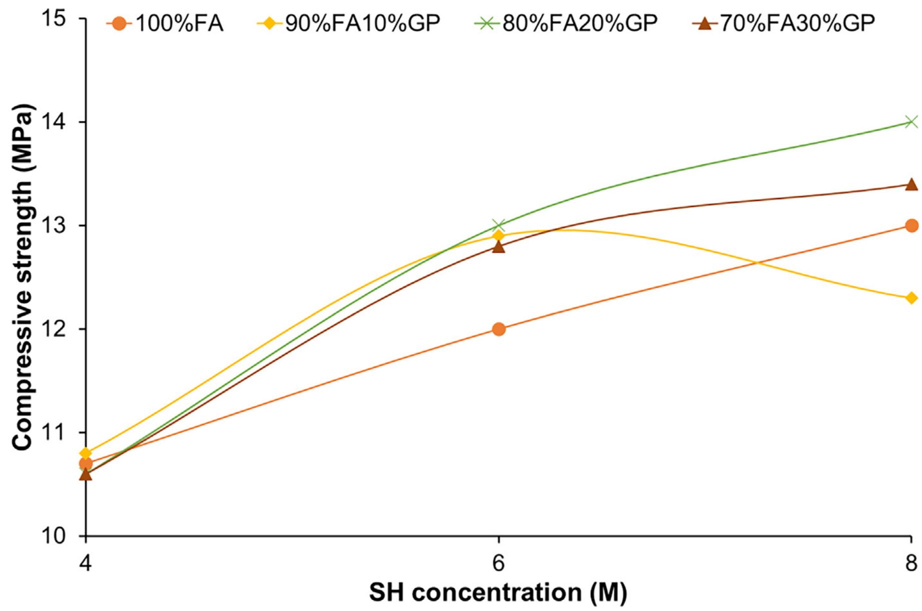

Fig. 10. Influence of precursor content and SH concentration (adapted from (Samarakoon et al., 2020)).

higher Si/Al ratio was linked to the reduction in the development of the network responsible for strength as a result of the delay in the amount of silicate integrated into the gel at latter reaction stages when there is no availability of aluminate. However, the lower reduction in the compressive strength (i.e. maximum reduction of 27.1%) was linked to the ability of the GP to act as micro fillers resulting in the densification of the AAM matrix. This observation is in agreement with that of Hao et al. (2013) where the effect of GP content and solid to liquid ratio on the compressive strength of AAMs were evaluated.

In contrast, the study by Redden and Neithalath (2014) showed that the use of GP to replace 50–100% FA resulted in an increase in the compressive strength for different initial curing temperatures. This contradicting observation could be due to the use of elevated curing and only sodium hydroxide as an activator compared to the studies discussed earlier. Similarly, the study by Novais et al. (2016) showed that the replacement of 12.5% GP with MK resulted in an enhancement in the compressive strength by 31.4%. However, the use of higher content of GP as a replacement of MK resulted in a decrease in the compressive strength. The initial increase in the compressive strength when 12.5% MK was replaced with GP was ascribed to the initial increase in the silicate to aluminate ratio beneficial to the strength formation. On the other hand, the decrease in the compressive strength higher content of GP (i.e. 25% to 50%) was linked to the higher amount of unreacted GP in the matrix and the reduction in the dissolution rate of the aluminate and silicate monomers. These observations are in agreement with that of Si et al. (2020b) where the use of GP more than 5% replacement of MK in AAMs resulted in a decrease in the compressive strength. Similarly, Jiang et al. (2020) reported a decrease in the compressive strength of AAMs when the content of GP used as a replacement of FA is greater than 20%.

Fig. 8 presents a general overview of the compressive strengths of AAMs made with GP as partial replacement of the conventional pre-

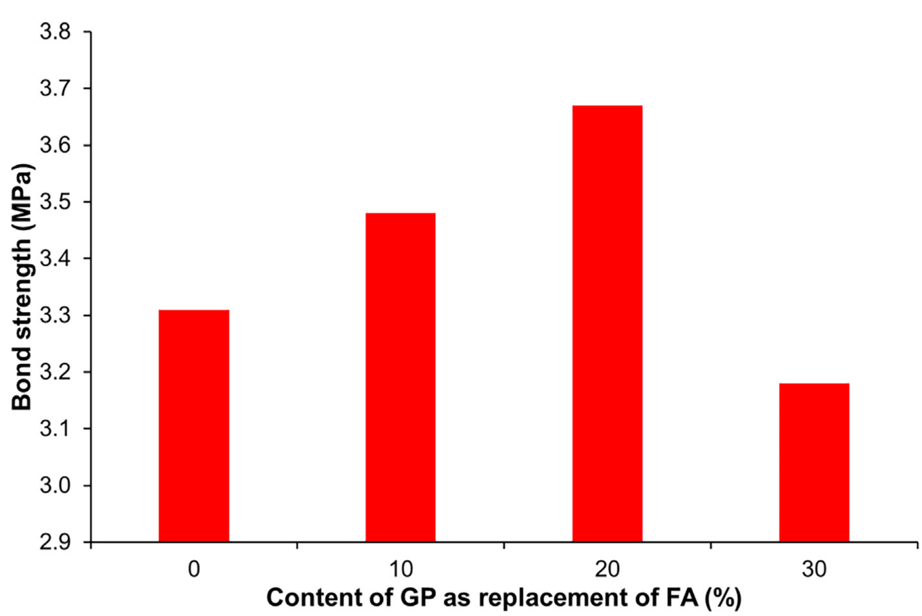

Fig. 11. Influence of GP content on bond strength (adapted from (Jiang et al., 2020)).

cursors (i.e. FA, SL and MK). The results presented in green lines in Fig. 8 represent those made with GP as partial replacement of MK while the results in red lines represent AAMs made with GP as partial replacement of SL. AAMs made GP as partial replacement of FA is represented in blue. The results presented in Fig. 8 should be compared for only GP content in each study rather than a comparison with other studies. The variation in the compressive strength of AAMs between the studies presented in Fig. 8 can be ascribed to the difference in composite type, type and concentration of activator and curing conditions.

Findings by Rivera et al. (2018) showed that the source of GP could influence the corresponding performance of GP-based AAMs despite the various GP having similar chemical compositions. The compressive strength at 28 days of GP sourced from the glass bottle, window glass and lamps are 54 MPa, 30 MPa and 24 MPa, respectively. The findings from the study further suggest that the use of SH concentration of 4 M is optimum as there was a reduction or no significant increase in the compressive strength when the concentration of SH was increased up to 10 M as presented in Fig. 9. The reduction in the compressive strength of GP-based AAMs when the concentration of the SH was increased was ascribed to the possible attack on the GP by the alkali resulting in the coating of the GP particles leading to lower reactivity (Cyr et al., 2012). The presence of excess silica and its corresponding mobility inhibition due to higher dissolution of the GP when a higher concentration of SH is used can also be linked to the reduction in compressive strength at higher SH concentration (Panias et al., 2007). In contrast, when GP was used alongside FA as the precursor, it was found out that the compressive strength of the AAMs increased with higher SH concentration (Samarakoon et al., 2020) as shown in Fig. 10. These results indicate that a higher concentration of SH is only beneficial when GP is used alongside other precursors.

3.5. Bond strength

The bond strength of construction materials indicates interaction with other materials such as steel reinforcement. The bond strength is a critical property of materials such as AAMs when they are used in reinforcement composites as it plays a significant role in the structural safety of the reinforced composite (Bingöl and Gül, 2009; Ergün et al., 2016). Jiang et al. (2020) investigated the bond strength of AAM made with GP as up to 30% replacement of FA. Similar to the compressive strength findings from the study, it was found out that the use of GP as a replacement of FA up to 20% resulted in an improvement in the bond strength. However, the use of higher content of GP (i.e. 30%) resulted in a decrease in the bond strength of the AAMs as shown in Fig. 11.

3.6. Flexural strength

The incorporation of GP as up to 30% replacement of SL as a precursor was found to result in an increase in the flexural strength of AAMs (Shoaei et al., 2020) as shown in Fig. 12. The use of GP as 30% replacement of SL as precursor resulted in an increase in flexural strength by 29%, 48%, 50% and 75% at 3 days, 7 days, 14 days and 28 days, respectively when compared to the control AAM with on SL as the precursor. The enhancement in the flexural strength when GP was incorporated up to 30% was linked to the introduction of additional sodium silicate gel into the matrix coupled with the refinement of the pores by unreacted GP (Redden and Neithalath, 2014). Microstructural investigation of the AAMs also indicated the use of GP as 30% replacement of the SL resulted in the refinement of the microstructure as shown in Fig. 13. However, the reduction in the flexural strength at higher content of GP (i.e. 40%) was ascribed to the lower reactivity of the GP compared to SL (Liu et al., 2019b). The bigger particle size of GP compared to that of SL has also been reported to be responsible for the reduction in the flexural strength due it its ability to limit the activation of the GP (Jiang et al., 2019). These observations are consistent with that of Liang et al. (2021) where the use of GP as a 20% replacement of MK was found to be optimum in terms of flexural strength. A similar observation was reported by Huseien et al. (2020) where nano GP was used as up to 20% replacement of the SL as the precursor. However, in the study by Huseien et al. (2020), the optimum nano GP content for flexural strength was 5% as there was a reduction in the flexural strength of the AAMs at higher contents (i.e. 10% to 20%).

In contrast, the study by Long et al. (2019) found out the use of GP to replace SL up to 70 % as a precursor in AAMs resulted in a decrease in the flexural strength as shown in Fig. 14. The reduction in the flexural strength of the AAMs with higher content of GP was ascribed to the lower reactivity of GP compared to that of SL. The reduction in the reactivity in the presence of GP was validated by the TGA/DTA analysis of AAM made with only SL as a precursor (P0) and that made with GP as 30% replacement of the SL (P30) as shown in Fig. 15. This

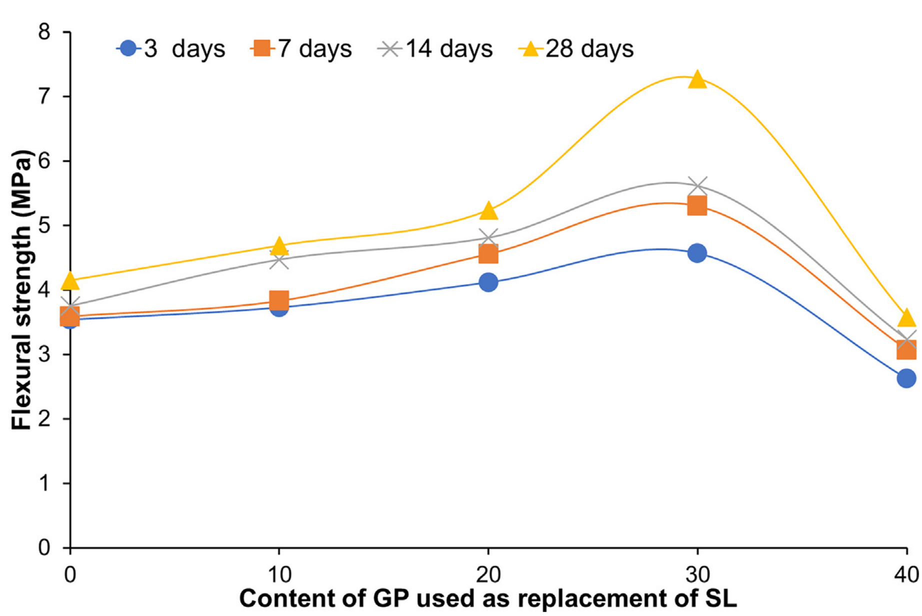

Fig. 12. Influence of GP content on flexural strength (adapted from (Shoaei et al., 2020)).

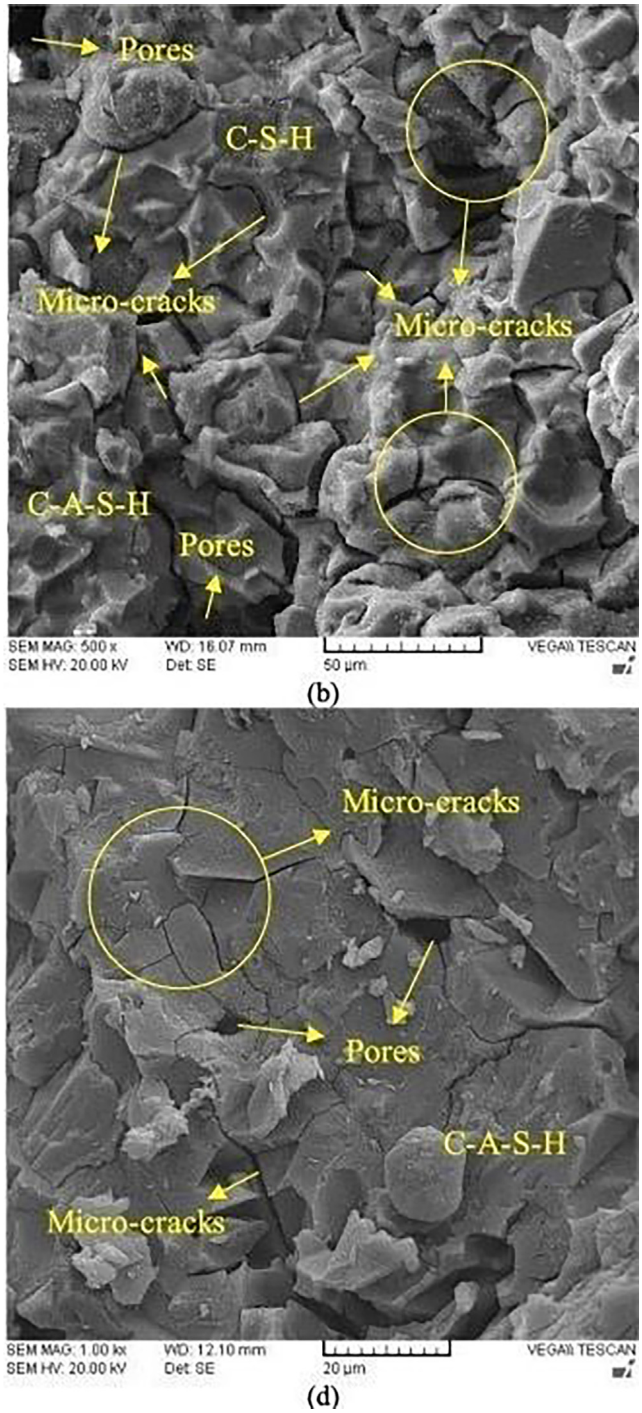

Fig. 13. Influence of GP content on microstructure (a) 100%SL (b) 70% SL30%GP (reused with permission (Shoaei et al., 2020)).

contradicting effect of GP on the flexural strength indicates the chemical properties of the precursor and the corresponding type and concentration of activator used would influence the mechanical properties of AAMs.

3.7. Tensile strength

In contrast to the majority of the compressive strength of GP-based AAMs, it has been found that the incorporation of GP as up to 30% replacement of FA as a precursor resulted in an increase in tensile strength (Samarakoon et al., 2020). As shown in Fig. 16, the tensile strength of the AAMs increased with GP content. However, the increase in the tensile strength is not significant at an early age (i.e. 7 days) compared to at later age (i.e. 56 days). This lower impact of the GP at early ages was ascribed to the partial hydration of the precursors (Samarakoon et al., 2020).

In another study, Huseien et al. (2020) reported an increase in the split tensile strength when nano GP was used as a 5% replacement of SL in AAMs. However, at higher content of GP (i.e. 10% to 20%), there was a reduction in the split tensile strength of the AAMs as shown in Fig. 17. The reduction in the tensile strength at higher nano GP content was linked to its higher surface area which result in limited water for the reaction thereby inhibiting the formation of products. A similar observation was reported by Marathe et al. (2021) where the use of more than 15% GP as replacement of the FA as precursor resulted in a decrease in the split tensile strength of AAMs activated with various silica modulus.

4. Applications of GP based AAMs

As it is evident that GP can be incorporated as a precursor to producing AAMs for various applications, some of the existing applications are briefly discussed:

4.1. Soil stabilization

In order to improve the sustainability of the conventional method used to improve soil stabilization, Pourabbas Bilondi et al., 2018 utilized GP-based AAM as a sustainable alternative to PC as a stabilizing agent for clayey soils. The GP was added up to 25% to the clay soil and activated with the conventional activators. Results from the study indicate the use of up to 15% GP resulted in an increase in the strength performance of the clayey soils. The enhancement in the performance of the clayey soil when the GP was incorporated was ascribed to the rich silica content of GP. Similar observations have been reported by Baldovino et al. (2021) where the use of GP-based AAM for soil stabilization was found to yield a more solid structure.

4.2. Road base stabilization

Similar to soil stabilization for soils, Xiao et al. (2020b) utilized GP-based AAM in the stabilization of road bases. The GP used was obtained from glass containers and used alongside FA as the precursor to produce AAM as a stabilization agent for road bases. Findings from the study showed that the presence of higher content of amorphous silica in the GP coupled with that in the FA resulted in an improvement in the strength performance of road bases.

4.3. Tiles

Rivera et al. (2018) utilized GP obtained from glass bottles, fluorescent lamps and soda-lime window glass in the production of AAM-based tiles. Findings from the study showed that titles with good mechanical performance can be produced with the use of only GP as the aluminosilicate precursor. Flexural load capacity up to 1006 N was achieved when the GP was used as a precursor. Fig. 18 shows the production process and flexural load evaluation of the GP AAMs-based titles.

4.4. Foam blocks

Thermal efficient AAM blocks were produced by Singh et al. (2021) by using GP and FA as precursors. The results from the study showed that thermal efficient blocks with compressive strength in the range of 15 MPa to 40 MPa and thermal conductivity in the range of 0.21 W/mK to 0.42 W/m.K can be produced with GP and FA as the precursor.

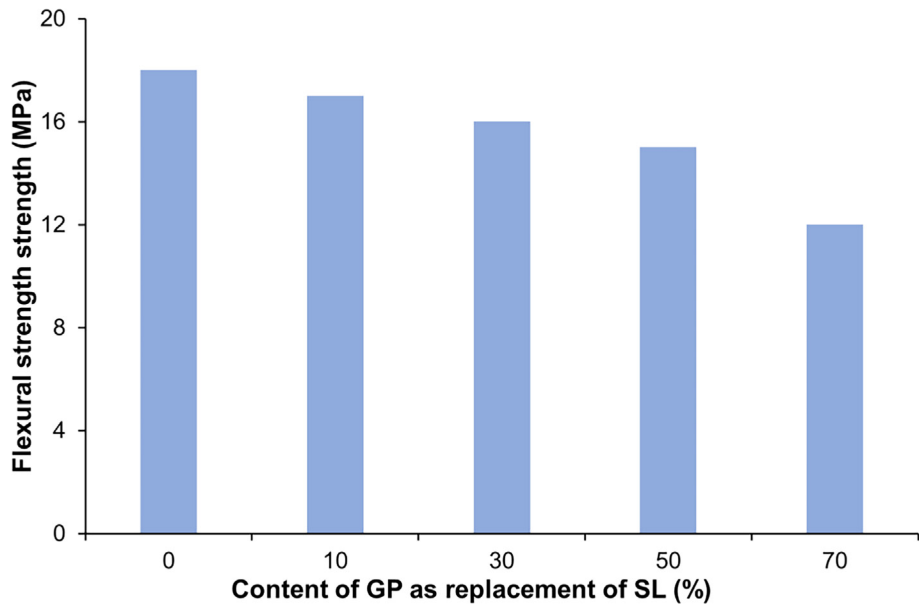

Fig. 14. Influence of GP content on flexural strength (adapted from (Long et al., 2019)).

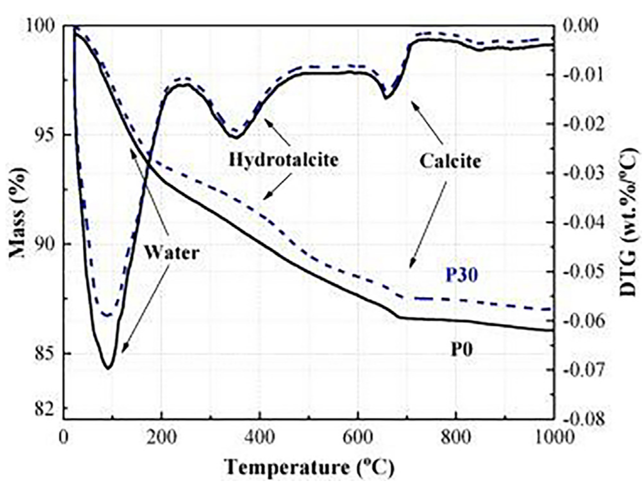

Fig. 15. TGA/DTG curve of AAMs (reused with permission (Long et al., 2019)).

5. Recommendations

The discussions presented in this paper showed that the content of GP used as a precursor in AAMs can be optimized to achieve desired fresh and mechanical properties. However, more research and development are still required in this area in order to propel the use of GP as a precursor in AAMs. The following areas are recommended for future studies:

1. As the use of glass products is known to cause an alkali-silica reaction (ASR) which is detrimental to the performance of AAMs, an extensive study should be carried out in this area to evaluate how various physical and chemical properties of GP would influence the ASR.
2. The majority of the studies on the use of GP as a precursor in AAMs have only focused on its mechanical properties. Thus, it is critical that additional performance evaluation of such AAMs should be carried out in terms of durability properties. These future durability studies should focus on tests such as freeze–thaw, wet-dry and acid resistance where the durability performance of these AAMs in aggressive environments can be evaluated.
3. A lifecycle assessment of AAMs incorporating GP as a precursor should also be carried out in order to effectively and efficiently evaluate the sustainability and economic benefits associated with its use.
4. In contrast to the conventional precursors such as FA and SL, there is limited understanding of the mechanism involved in the alkali activation of GP. Thus, various microstructural studies should be carried out to understand the reaction kinetics that occurs during the activation of GP. The reaction kinetics of GP activation should also be linked with its physical properties.

6. Conclusions

This paper presents an overview of the fresh and mechanical properties of AAMs made with GP as a precursor. Based on the discussion made in this paper, the following conclusions can be drawn:

1. GP from various sources can be utilized solely or alongside other precursors to produce AAMs with acceptable properties for various applications.
2. The use of GP as a replacement for conventional precursors resulted in an increase in the workability of AAMs. The improvement in workability when GP is used as the precursor can be linked to the smooth and glossy surface of the GP particles which reduced the amount of water absorbed and provided additional water available to reduce the interparticle friction.
3. The use of GP as a precursor in AAM would result in an extension in the set times due to the lower reactivity of GP compared to other conventional precursors. In cases where shorter set times are required; the content of GP could be reduced or other initiatives such as the use of elevated curing and higher alkali concentration can be employed.
4. There is no consensus on the influence of GP on the mechanical properties of AAMs. Some studies reported an increase in the mechanical performance up to an optimum content while others reported a reduction in the mechanical performance with higher GP content. These findings indicate that the physical and chemical

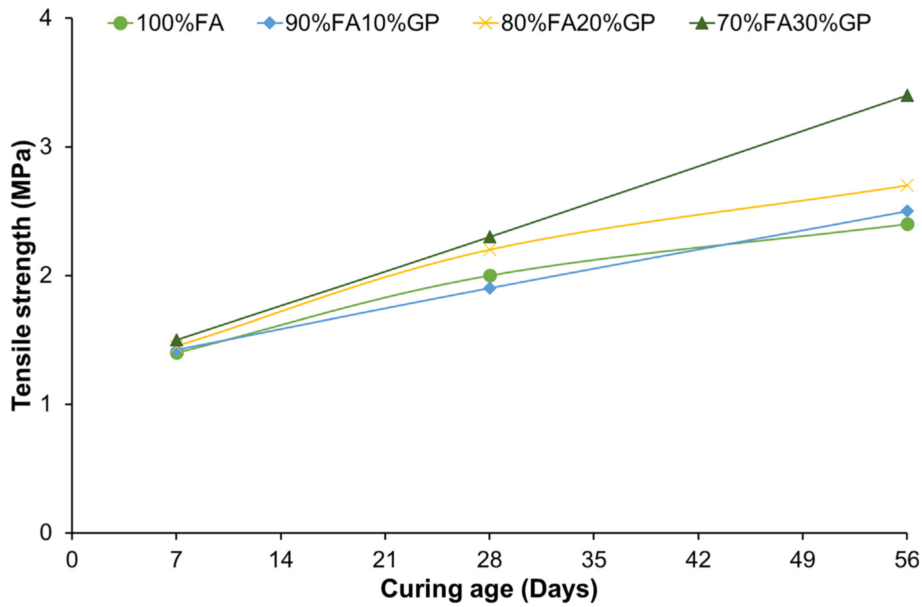

Fig. 16. Influence of precursor content and curing age adapted from (Samarakoon et al., 2020)).

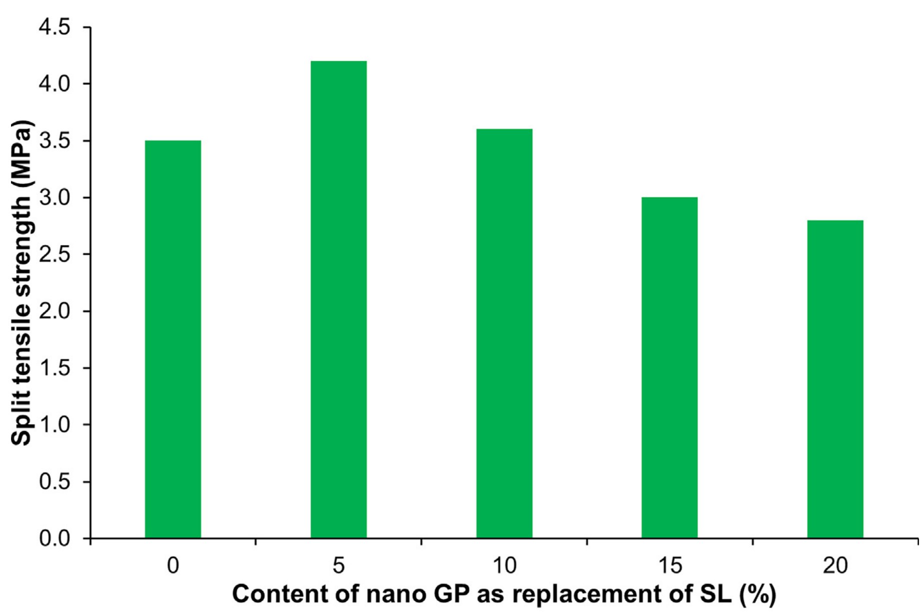

Fig. 17. Influence of nano GP content on flexural strength (adapted from (Huseien et al., 2020)).

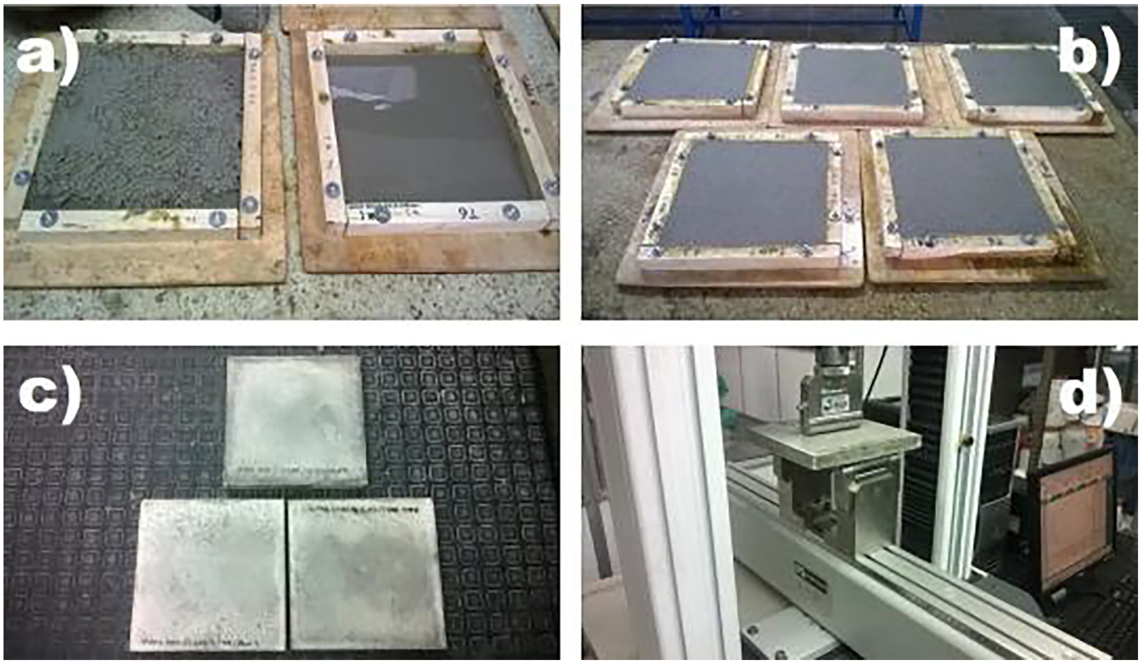

Fig. 18. Production of titles with GP AAM (reused with permission (Rivera et al., 2018)).

properties of GP would have a significant influence on the corresponding mechanical performance. Thus, it is recommended that trial tests should be carried out before large-scale applications in order to optimize the content of GP for various applications.

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 paper.

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