Influence of Fibres on the Strain Hardening Behaviour of Ultra-High-Performance Geopolymer Concrete: A Review

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Abstract. Continuous cement manufacturing has increased the percentage of CO_2 emitted into the air, thereby increasing the problem of global warming and its damaging effects on the environment. Therefore, adopting a more sustainable strategy to replace conventional concrete has become essential. Geopolymer concrete (GPC) is a relatively new engineering material that is sustainable and innovative and has several advantages over conventional cement concrete. The use of supplementary cementitious materials mixed with alkali-activated solutions can be substituted for cement in GPC manufacturing. Generally, "ultra-high-performance concrete" (UHPC) is referred to as a composite material made from ordinary Portland cement (OPC) with better durability, compressive strength which is extremely high, and toughness. Recently, studies have been conducted to develop UHPC using geopolymer technology with a performance comparable to that of UHPC. However, comparable to UHPC, ultra-high-performance geopolymer concrete (UHPGPC) without fibres may show significant brittleness with the strength increase. The intrinsic brittle nature of concrete can lead to the cracking and eventual failure of concrete structures. Consequently, it becomes necessary to add fibres to increase the ductile performance of UHPGPCs. To enhance the practical uses of UHPGPCs and improvement in fundamental knowledge of material testing requirements and procedures, a detailed analysis of the strain-hardening properties of UHPGPCs is necessary. As a result, the impact of fibres on the strain-hardening behaviour of GPCs and UHPGPCs is thoroughly reviewed in this work. The findings of this research will serve as an essential foundation for designing and developing UHP-GPC with better strain-hardening behaviour.

Keywords: Geopolymer concrete · strain hardening · fibre reinforcement · ultra-high-performance geopolymer concrete

1 Introduction

"Ultra-high performance concrete" (UHPC) can be defined as a Portland cement-based substance having exceptional properties like compressive strength above 150 MPa, more resistance to fracture (high toughness), improved tensile ductility, and improved durability [1]. UHPC generally contains a significant amount of Portland cement (800–1100

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kg/m^3), which can lead to substantial greenhouse gas emissions [1]. However, because of the considerable amount of energy usage and emissions of CO_2 associated with the manufacturing of Portland cement, continuous Portland cement use reduces the sustainability of UHPC [2]. According to studies, generating 1.5 tonnes of clinker requires 10 MJ of energy and emits around 1.2 tonnes of CO_2 into the atmosphere. However, because of the high energy consumption significantly and the association of carbon emissions with the production of Portland cement, continuous Portland cement use reduces the sustainability of UHPC. The sustainability of building materials in building development can be achieved by replacing ordinary Portland cement with different low-carbon binders [3]. Therefore, researchers have been striving to minimize the quantity of cement and natural resource materials used to manufacture concrete mixes by substituting supplementary cementitious and waste materials including industrial byproducts and biomass residues to replace Portland cement and aggregates [4].

Recently, attempts have been made to develop UHPC using geopolymer binders. This novel material has similar performances to UHPC. Geopolymer binders with comparable or superior properties to ordinary Portland cement are recently gaining popularity. Geopolymer binders are clinker-free, employing source materials combined with an alkaline activator as binders. Generally, the source materials utilised are aluminosilicates, for example, powdered granulated blast furnace slag (GGBS), metakaolin, waste glass, fly ash, etc. [4]. Sodium elements in the form of hydroxide and silicate are mostly used as alkaline activators. According to Zhang et al. [5], the unit energy consumption and greenhouse gas emissions of geopolymer binder materials were nearly 60% lower than that of Portland cement. Many researchers have investigated the performance of Ultra-High-Performance Geopolymer Concrete (UHPGPC) as a promising candidate for concrete, greener UHPC material. Because the alkali-activation method increases its strength, UHPGPC may be able to replace UHPC in structural applications, making them more durable and sustainable.

As in the majority of studies, UHPGPC is produced by combining solid precursors with activator solutions and steel fibre content with fine quartz sand and a minimum liquid-to-binder (or w/b) ratio [6]. However, the combination of different solid precursors is frequently employed to improve the polymerized contents of geopolymeric binders because they typically have a substantially higher porosity than conventional UHPC [7]. Additionally, ultra-high performance and high-strength concrete have different rheological characteristics from conventional concrete, thus, the addition of high-range water-reducing agents into the concrete typically does not significantly impact the lowering of the overall w/b ratio, a vital element in its manufacturing. Moreover, compared to conventional concrete and UHPC, plain UHPGPC may show significant brittleness with improved strength characteristics. As a result, in ultra-high performance and high-strength concrete made from geopolymers, the improvement in mechanical characteristics often depends on microstructural development and fibre presence. Consequently, it becomes necessary to add fibres to enhance UHPGPC's ductility. Additionally, fibres can change brittle failure into ductile failure and provide strain-hardening characteristics to UHPC in tension. Either natural or synthetic fibres can be employed in all various forms of concrete, including UHPGPC. The incorporation of fibres into concrete improves impact resistance at room temperature, reduces plastic shrinkage, and improves ductility and mechanical strength [8].

As a result, UHPGPC is the perfect material to provide more strength and durability to components or structures. Even though there are many studies available on the mechanical strength and durable characteristics of UHPGPCs, however, the studies on the effect of fibres on the strain-hardening behaviour of UHPGPCs are limited. Therefore, this review paper investigates the impact of fibres on the strain-hardening behaviour of fibre-reinforced UHP GPC. Also, the mechanical strength and strain-hardening characteristics of conventional strain-hardening concrete and UHP strain-hardening GPC were compared.

2 Mechanical Strength of Strain Hardening GPC and UHP Strain Hardening GPC

Numerous researchers have investigated the impacts of different geopolymer binder materials, fine aggregates, and fibres on the mechanical strength characteristics of strain-hardening GPC and ultrahigh-performance strain-hardening GPC. The impact of binder materials, alkali activators and fibres on the mechanical strength performance of conventional GPC and UHPGPC are presented in the flowing session.

2.1 Influence of Binder Materials and Alkali Activators

The performance of individual binder materials and the combination of various binder materials and various alkali activators on the compressive strength of various kinds of GPC mixes were extensively presented in this session. Nematollahi et al. [9] developed a 2% of polyvinyl alcohol (PVA) fibre-incorporated strain hardening geopolymer matrix using low calcium class F fly ash and studied the effect of potassium (K) and sodium (Na) based alkali activators on its mechanical strength characteristics. The compressive strength value for the sodium-based alkali activator GPC was observed to be 63.7 MPa, which is higher than the values for the K-based alkali-activated matrix and the conventional strain-hardening matrix. Similarly, using a sodium-based alkali activator in GPC developed from metakaolin [10] showed a maximum strength of 77.56 MPa and was comparatively better than K-based GPC from metakaolin. The Na-based alkaline activators are generally preferable to the K-based activator combination due to their minimum cost and higher gain in compressive strength. However, instead of metakaolin, Nematollahi et al. [11] studied the strength of GPC made from fly ash, PVA fibres, and quartz sand as in Trindade et al. [10]. A maximum strength value of 56.8 MPa was observed and was found to be lower than that given by metakaolin-based GPC [10]. Additionally, Wang et al. [12] studied the combined effect of fly ash and GGBS, yielding a modest performance of 32 MPa as compressive strength. The variation in compressive strength of strain-hardening GPC using different alkaline solutions and binder materials is shown in Fig. 1.

In addition, the performance of ultrahigh-performance strain hardening GPC can also be influenced by the difference in the material compositions, which is presented in Fig. 2. Generally, the ultrahigh performance GPC is developed by combining fly ash, GGBS,

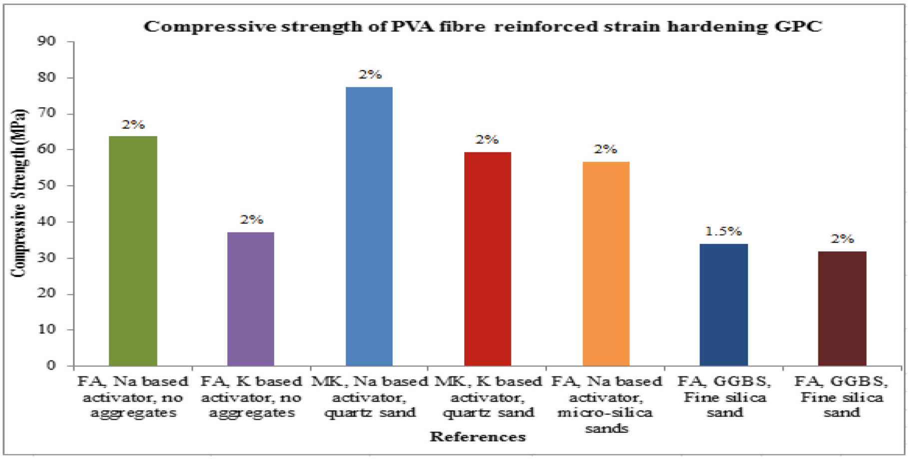

Fig. 1. Compressive strength variation in strain hardening GPC with different binder materials and alkaline activator solutions

silica fume, silica sand, and steel fibres. Zhang et al. [13] investigated the performance of ultrahigh-performance GPC developed by using fly ash, GGBS, silica fume, normal river sand instead of silica sand, and 3% of steel fibre and obtained a compressive strength value of 170.4 MPa. However, Mousavinejad and Sammak [14] developed a binary blend of GPC from GGBS and silica fume reinforced with 2% steel fibre without incorporating fly ash. Comparatively better strength of 150.61 MPa was observed even without adding fly ash and only 2% fibre reinforcement. Akeed et al. [15] and Shi et al. [16] utilized the general constituents of ultrahigh performance GPC such as fly ash, GGBS, silica fume, silica sand, and 3% steel fibre and found maximum compressive strength values of 150.5 MPa and 155 MPa, respectively. In addition, Ambily et al. [17] also used the same mixtures as that of Akeed et al. [15] and Shi et al. [16] with 1% of steel fibre but attained a strength value of 175 MPa, which was higher than that observed in other studies [15, 16]. Furthermore, Yu et al. [18] conducted studies on UHPGPC produced from fly ash, GGBS, limestone powder instead of silica fume, and the combination of silica sand and normal sand as aggregates with 1% of steel fibre inclusion. It was noticed that comparatively lesser values of 90 MPa and 95 MPa with different steel fibre lengths. Hence, the ternary blend of fly ash, GGBS, and silica fume, along with silica sand as fine aggregate and steel fibre as reinforcement, can be considered the better choice of materials to develop UHPGPC. In the case of conventional strain hardening GPC, the presence of fly ash, GGBS, and silica sand with PVA fibre addition was utilized by many researchers. However, the use of metakaolin also proved to perform better than any other fly ash and GGBS combinations. Moreover, a sodium-based alkali activator solution is the wise choice to develop GPC, irrespective of the type of source materials used. The usefulness of hybridization of 1.75% of large diameter steel fibres and 0.25% of PPF in developing UHPGPC was studied by Mousavinejad and Sammak [14] and resulted in good strength values of 146.12 MPa but lower than specimens reinforced with steel fibre only. However, the obtained values proved better than GPC mixes reinforced with only large-diameter steel fibres. Hence, the adverse effects of large-diameter steel fibres on the compressive strength of UHPGPC (shown in Fig. 2) can be reduced by hybridizing it with a small percentage of PPF. The difference in compressive strength gain of strain-hardening GPC and strain-hardening UHP-GPC with the hybridization of various fibres is shown in Fig. 3.

Furthermore, among the studied UHP-GPC, the improved flexural strength value of 13.5 MPa was shown by the specimens reinforced with 1% of small diameter steel fibres incorporated with fly ash, GGBS, silica fume and silica sand [17] followed by mixes reinforced using larger diameter steel fibres as well as hybridized steel and PP fibres

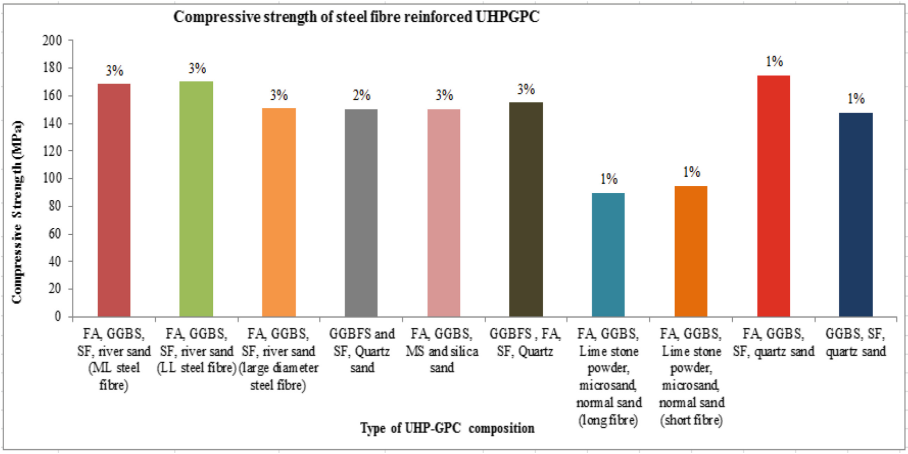

Fig. 2. The influence of various component materials of strain hardening UHP-GPC on compressive strength performance

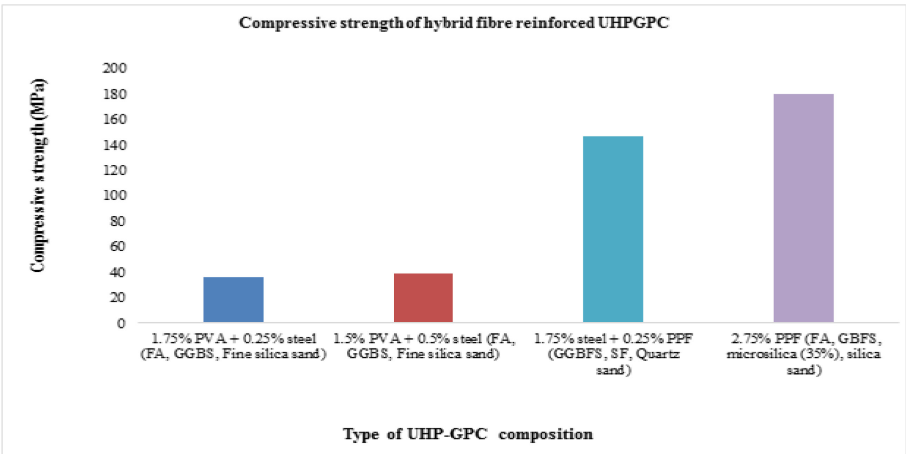

Fig. 3. The effect of hybridization of different fibres on the compressive strength of strain-hardening GPC and UHP-GPC

[14]. In contrast to the observation on compressive and flexural strengths, the highest modulus of elasticity values was exhibited by larger diameter steel fibres with materials like GGBS, silica fume, and silica sand without adding fly ash [14]. The hybridization of steel and PP fibres [14], as well as the reinforcement using PP fibre alone [19] improved the modulus of elasticity values. Also, they performed well over small diameter steel fibre reinforced UHP-GPC mix containing fly ash, GGBS, silica fume, and silica sand [15] and Shi [16]. The impacts of various binders and fibre materials on the mechanical strength characteristics of strain-hardening GPC and strain-hardening UHP-GPC are shown in Tables 1 and 2, respectively.

2.2 Effect of Fibres on Compressive Strength Performance

The fibres are the critical component in strain-hardening GPC and ultrahigh-performance GPC. The percentage incorporation of these fibre materials is proven to affect the mechanical strength characteristics of the resultant mixes. Generally, researchers mostly use PVA fibres in conventional strain-hardening concrete and strain-hardening GPC. The increase in PVA fibre concentration by up to 2% improved the compressive strength in many studies [9–11]. In addition, the utilization of hybridized PVA fibres and recycled tyre steel fibres [12] improved the compressive strength values. The strength values enhanced with the more percentage incorporation of steel fibres because of their high stiffness and hydrophilic properties, which allow them to absorb more energy and create a strong fibre-matrix contact. Instead of the optimum 2% addition of PVA fibres, a length of 8 mm or 12 mm and a diameter of 40 μm were mainly utilized in most studies. The effect of various fibres on the mechanical strength performances of strain-hardening GPC and strain-hardening UHP-GPC is shown in Tables 1 and 2, respectively.

Zhang et al. [13] studied how the differences in lengths and diameters of steel fibres influence the performance of UHPGPC. As a result, an improvement in strength was noticed with the increment of the steel fibre content and length and the decrease in fibre diameter. Moreover, the most popular fibre reinforcing method for creating UHPGPC continues to be using straight steel fibres with a length of 13 to 15 mm and a diameter of 0.16 to 0.20 mm. In addition, the steel fibres with hook ends and corrugated shapes were observed to perform inferiorly to straight steel fibres. In contrast to the conventional way of developing strain-hardening ultrahigh-performance GPC using steel fibres, Bakar et al. [19] studied the suitability of polypropylene fibre (PPF) in developing UHPGPC using fly ash, GGBS, and micro silica. It was noticed that comparatively better results over steel fibre reinforced UHPGPC on compressive strength of about 180 MPa with 35% incorporation of micro silica sand and 2.75% of PPF addition. The PPF serves as a bridging agent in the concrete production process by forming a strong core inside the concrete specimen during compression and primarily enhances the compressive behaviour of UHPGPC by inhibiting lateral expansion.

Table 1. Mechanical strength properties of strain hardening GPC

Type of fibre used	Source materials	Percentage addition of fibres	In-use Dimensions	Compressive strength (MPa)	Flexural strength (MPa)	Modulus of Elasticity (GPa)	Ref.
PVA	low calcium fly ash, Na-based activator, matrix (no aggregates)	2%	Length: 8 mm Diameter: 40 μm	63.7	-	8.5	
PVA	low calcium fly ash, K-based activator, matrix (no aggregates)	2%	Length: 8 mm Diameter: 40 μm	37.3	-	5.2	
PVA	metakaolin and Fine-grained quartz sand, Na-based activator	2%	Length: 12 mm Diameter: 40 μm	77.56	-	10.94	
PVA	metakaolin and Fine-grained quartz sand, K-based activator	2%	Length: 12 mm Diameter: 40 μm	59.43	-	10.17	
PVA	fly ash and micro-silica sands, Na-based activator	2%	Length: 8 mm Diameter: 40 μm	56.8	-	-	
PVA	fly ash, GGBS, Fine silica sand	1.50%	Length: 12 mm Diameter: 40 μm	34	6	-	
PVA	fly ash, GGBS, Fine silica sand	2%	Length: 12 mm Diameter: 40 μm	32	8.6	-	

(*continued*)

Table 1. (*continued*)

Type of fibre used	Source materials	Percentage addition of fibres	In-use Dimensions	Compressive strength (MPa)	Flexural strength (MPa)	Modulus of Elasticity (GPa)	Ref.
PVA + Steel	fly ash, GGBS, Fine silica sand	1.75% PVA + 0.25% steel	PVA (Diameter: 40 μm,), Steel (Diameter: 150 μm, Length: 20 mm	36	6.6	-	
PVA + Steel	fly ash, GGBS, Fine silica sand	1.5% PVA + 0.5% steel	PVA (Diameter: 40 μm, Length: 12 mm), Steel (Diameter: 150 μm, Length: 20 mm	39	6.4	-	

3 Strain Hardening Behaviour of UHP GPC

The first crack and the ultimate crack strength of strain hardening GPC, as well as ultrahigh performance strain hardening GPC, is necessary to analyze the strain hardening performance of the developed specimens. Also, the ultimate crack strength should always be greater than the initial crack strength to achieve the strain-hardening property. The findings of the uniaxial tension test, including the first-crack strength, the measured ultimate tensile strength, and the tensile strain capacity, are essential to understand the strain-hardening performance of different types of GPC specimens. Several studies [9–11] on strain hardening GPC developed from fly ash, metakaolin, fly ash, and GGBS combinations reinforced with PVA fibres were observed with improved ultimate crack strength over the first crack strength and is graphically shown in Fig. 4.

Moreover, it was noticed that the specimens formed from fly ash and micro silica sand, along with PVA fibre addition, showed better strain hardening characteristics such as first and ultimate crack strength. However, a better tensile strain capacity of 4.76% was exhibited by metakaolin-based GPC specimens. Also, similar to the observation on compressive strength of ultrahigh performance strain hardening GPC, an increase in length and decrease in the diameter of the steel fibres reduced the first and ultimate crack strength of the specimens and is shown in Fig. 5.

The first and ultimate crack strength of specimens developed from the same binder materials and different fine aggregates, such as river sand and quartz sand, were studied by [13] and [16], respectively. Better strength performances were noticed in the mix

Table 2. Mechanical strength properties of ultra-high performance strain hardening GPC

Type of fibre used	Source materials	Percentage addition fibres	In-use Dimensions	Compressive strength (MPa)	Flexural strength (MPa)	Modulus of Elasticity (GPa)	Ref.
Steel (medium length)	Slag, fly ash and silica fume, river sand	3%	Length: 8 mm Diameter: 0.12 mm	168.5	-	-	
Steel (large length)	slag, fly ash and silica fume, river sand	3%	Length: 13 mm Diameter: 0.12 mm	170.4	-	-	
Steel (Large diameter)	slag, fly ash and silica fume, river sand	3%	Length: 13 mm Diameter: 0.20 mm	150.8	-	-	
Steel fibre	GGBS and silica fume, Quartz sand	2%	Length: 13 mm Diameter: 0.20 mm	150.61	12.8	47.64	
Steel	Fly ash, GGBS, and microsilica, silica sand	3%	Length: 15 mm Diameter: 0.12 mm	150.5	15.1	31	
Steel	GGBS, class F fly ash, silica fume, Quartz sand	3%	Length: 13 mm Diameter: 0.12 mm	155	11.82	30.5	
Steel	fly ash, GGBS, Limestone powder, microsand, normal sand	1%	Length: 13 mm Diameter: 0.20 mm	90	-	-	

(*continued*)

Table 2. (*continued*)

Type of fibre used	Source materials	Percentage addition fibres	In-use Dimensions	Compressive strength (MPa)	Flexural strength (MPa)	Modulus of Elasticity (GPa)	Ref.
Steel	fly ash, GGBS, Lime stone powder, microsand, normal sand	1%	Length: 6 mm Diameter: 0.16 mm	95	-	-	
Steel	Fly ash, GGBS, Silica fume, quartz sand	1%	Length: 6 mm Diameter: 0.16 mm	175	13.5	-	
Steel	GGBS, Silica fume, quartz powder	1%	Length: 10 mm Diameter: 0.15 mm	148	-	-	
PPF	Fly ash, GGBS, and microsilica (35%), silica sand	2.75%	Length: 50 mm Diameter: 0.032 mm	180	-	45	
PPF + Steel	GGBFS and silica fume, Quartz sand	1.75% steel + 0.25% PPF	steel (Diameter: 0.20 mm, Length: 13 mm), PPF (Diameter: 0.035 mm, Length:6 mm)	146.12	12.62	47.11	

containing river sand as aggregates instead of quartz sand. It was proven that under tensile loading, the fibre reinforcement was successful in assuring strain hardening response followed by the formation of repeated multiple cracks. The strain hardening behaviour of GPC and UHPGPC, studied by different researchers, developed from different binders and fibres was explained through the investigation on first crack strength, ultimate crack strength and tensile strain capacity and is depicted in Table 3.

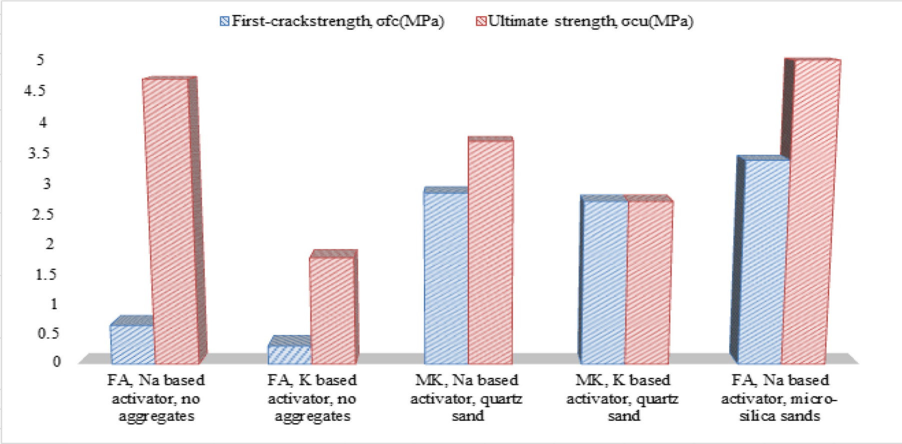

Fig. 4. First and ultimate crack strength gain in strain hardening GPC

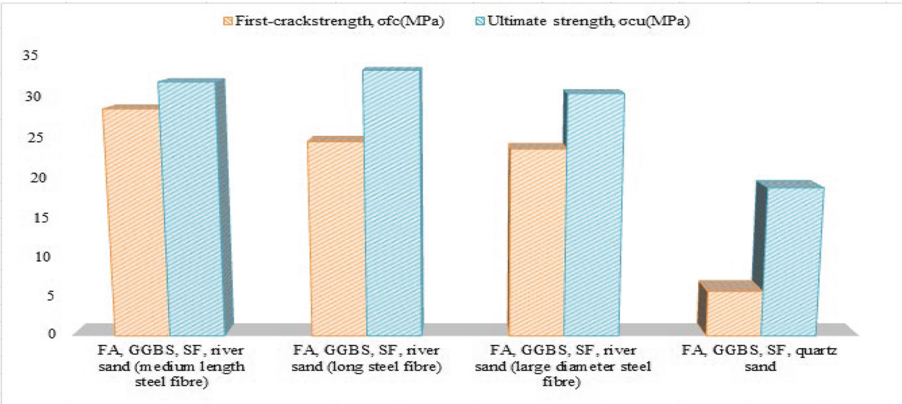

Fig. 5. Strain hardening behaviour of UHP-GPC reinforced with steel fibres of different lengths and diameter

4 Fracture Behaviour of UHP GPC

The stress concentration at the crack tip when the crack first begins to propagate is measured by fracture toughness [21]. Additionally, according to Nematollahi et al. [9], the coarse particles' texture, angularity, size and the paste microstructure can affect the fracture toughness of concrete. The fracture toughness values of strain-hardening GPC formed from sodium-based alkali-activated fly ash reinforced with PVA fibres [9] were dominant (0.436 MPa·m1/2) over a mix containing K-based alkali activators. However, in the metakaolin-based GPC [10], the K-based alkali-activated mix showed a higher fracture toughness value of 0.25 MPa·m1/2. The variation in the fracture toughness of PVA fibre-reinforced strain hardening GPC activated using sodium and the potassium-based alkaline solution is represented in Table 3.

Table 3. Strain hardening behaviour of conventional strain hardening GPC and UHP strain hardening GPC

Type of fibre used	Source materials	Percentage addition of fibres	In-use Dimensions	First-crack strength, σ_{fc} (MPa)	Ultimate strength, σ_{cu} (MPa)	Tensile strain capacity, ε_{cu} (%)	Fracture Toughness (MPa·m$^{1/2}$)	Ref.
PVA	low calcium fly ash, Na based activator, matrix (no aggregates)	2%	Length: 8 mm Diameter: 40 μm	0.66	4.7	4.3]	0.436	
PVA	low calcium fly ash, K based activator, matrix (no aggregates)	2%	Length: 8 mm Diameter: 40 μm	0.31	1.8	2	0.237	
PVA	metakaolin and Fine-grained quartz sand, Na based activator	2%	Length: 12 mm Diameter: 40 μm	2.87	3.71	4.76	0.15	
PVA	metakaolin and Fine-grained quartz sand, K based activator	2%	Length: 12 mm Diameter: 40 μm	2.73	2.73	-	0.25	
PVA	fly ash and micro-silica sands, Na-based activator	2%	Length: 8 mm Diameter: 40 μm	3.4	5	3.6	-	
Steel (medium length)	slag, fly ash and silica fume, river sand	3%	Length: 8 mm Diameter: 0.12 mm	28.6	31.9	-	-	
Steel (large length)	slag, fly ash and silica fume, river sand	3%	Length: 13 mm Diameter: 0.12 mm	24.6	33.3	-	-	

(*continued*)

Table 3. (*continued*)

Type of fibre used	Source materials	Percentage addition of fibres	In-use Dimensions	First-crack strength, σ_{fc} (MPa)	Ultimate strength, σ_{cu} (MPa)	Tensile strain capacity, ε_{cu} (%)	Fracture Toughness (MPa·m$^{1/2}$)	Ref.
Steel	slag, fly ash and silica fume, river sand	3%	Length: 13 mm Diameter: 0.20 mm,	23.7	30.5	-	-	
Steel	GGBS, class F fly ash, silica fume, Quartz sand	3%	Length: 13 mm Diameter: 0.12 mm	5.75	18.9	30.5	-	[16].

5 Conclusion

Improving the strain-hardening behaviour of concrete is one of the most critical aspects of developing UHP-GPC. This study involved a thorough evaluation of the literature on the effect of various binder materials and fibres on the strain-hardening behaviour of UHPGPC as well as conventional strain-hardening GPC. Based on the summary and discussion, the conclusions are as follows:

The strain-hardening development of geopolymer concrete with ultra-high-performance predominantly used the combination of fly ash, GGBS, silica fume, silica sand, and steel fibre reinforcement.
The length of the steel fibre strongly influenced the UHPC characteristics rather than the type or the quantity of fibre employed.
The compressive strength improvement was noticed in long steel fibres with a small diameter.
The most common fibre reinforcing technique used to design UHPGPC continues to be straight steel fibres with a length of 13 to 15 mm and a diameter of 0.16 to 0.2 mm.
The sodium-based activator combination is preferable over the potassium-based activator combination due to its lower cost and higher compressive strength gain.
The increase in length and decrease in the diameter of the steel fibres also reduced the specimens' first and ultimate crack strength.
The adverse effects of large-diameter steel fibres on the compressive strength and first and ultimate crack strength of UHP-GPC were reduced by hybridizing it with a small percentage of polypropylene fibres.
The UHP-GPC with a 2 to 3 volume percentage of steel fibres and strain hardening GPC with 2% of PVA fibres exhibited the highest mechanical strength.
Ultra-high performance and high-strength geopolymers have been developed using a steel and polymeric fibre hybrid.

References

1. Liu, Y., Zhang, Z., Shi, C.: Development of ultra-high performance geopolymer concrete (UHPGC): Influence of steel fibre on mechanical properties. Cem Concr Compos 112:103670 (2020).
2. Yu, R., Spiesz, P., Brouwers, HJH.: Mix design and properties assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). Cem Concr Res 56:29–39 (2014).
3. Shi, C., Qu, B., Provis JL.: Recent progress in low-carbon binders. Cem Concr Res 122:227–250 (2019).
4. Asrani, NP., Murali, G., Parthiban, K.: A feasibility of enhancing the impact resistance of hybrid fibrous geopolymer composites: Experiments and modelling. Constr Build Mater 203:56–68 (2019).
5. Zhang, J., Shi, C., Zhang, Z., Ou, Z.: Durability of alkali-activated materials in aggressive environments: A review on recent studies. Constr Build Mater 152:598–613 (2017).
6. Nodehi, M., Aguayo, F.: Ultra high performance and high strength geopolymer concrete. Journal of Building Pathology and Rehabilitation 6 (2021).
7. Provis, JL., Myers, RJ., White, CE.: X-ray microtomography shows pore structure and tortuosity in alkali-activated binders. Cem Concr Res 42:855–864 (2012).
8. Mostafa, SA., Tayeh, BA., Almeshal, I.: Investigation the properties of sustainable ultra-high-performance basalt fibre self-compacting concrete incorporating nano agricultural waste under normal and elevated temperatures. Case Studies in Construction Materials 17:e01453 (2022).
9. Nematollahi, B., Asce, SM., Sanjayan, J.: Tensile Strain Hardening Behavior of PVA Fiber-Reinforced Engineered Geopolymer Composite (2015).
10. Constâncio Trindade, AC., Curosu, I., Liebscher, M.: On the mechanical performance of K- and Na-based strain-hardening geopolymer composites (SHGC) reinforced with PVA fibres. Constr Build Mater 248 (2020).
11. Nematollahi, B., Ranade, R., Sanjayan, J., Ramakrishnan, S.: Thermal and mechanical properties of sustainable lightweight strain hardening geopolymer composites. Archives of Civil and Mechanical Engineering 17:55–64 (2017).
12. Wang, Y., Chan, CL., Leong, SH., Zhang, M.: Engineering properties of strain hardening geopolymer composites with hybrid polyvinyl alcohol and recycled steel fibres. Constr Build Mater 261 (2020).
13. Liu, Y., Zhang, Z., Shi, C.: Development of ultra-high performance geopolymer concrete (UHPGC): Influence of steel fibre on mechanical properties. Cem Concr Compos 112 (2020).
14. Mousavinejad, SHG., Sammak, M.: Strength and chloride ion penetration resistance of ultra-high-performance fibre reinforced geopolymer concrete. Structures 32:1420–1427 (2021).
15. Aisheh, YIA., Atrushi, DS., Akeed, MH.: Influence of steel fibres and micro silica on the mechanical properties of ultra-high-performance geopolymer concrete (UHP-GPC). Case Studies in Construction Materials 17 (2022).
16. Liu, Y., Shi, C., Zhang, Z.: Mechanical and fracture properties of ultra-high performance geopolymer concrete: Effects of steel fibre and silica fume. Cem Concr Compos 112:103665 (2020).
17. Ambily, PS., Ravisankar, K., Umarani, C.: Development of ultra-high-performance geopolymer concrete. Magazine of Concrete Research 66:82–89 (2014).
18. Gao, X., Yu, QL., Yu, R., Brouwers, HJH.: Evaluation of hybrid steel fiber reinforcement in high performance geopolymer composites. Materials and Structures/Materiaux et Constructions 50 (2017).
19. Tayeh, BA., Akeed, MH., Qaidi, S., Bakar, BHA.: Influence of microsilica and polypropylene fibers on the fresh and mechanical properties of ultra-high performance geopolymer concrete (UHP-GPC). Case Studies in Construction Materials 17 (2022).

20. Kathirvel, P., Sreekumaran, S.: Sustainable development of ultra high performance concrete using geopolymer technology, Journal of Building Engineering 39 (2021).
21. Ohno M., Li VC.: An integrated design method of Engineered Geopolymer Composite. Cem Concr Compos 88:73–85 (2018).