Proceedings of the 8th International Conference on Civil Structural and Transportation Engineering (ICCSTE'23)
Canada – June 04-06, 2023
Paper No. 113
DOI: 10.11159/iccste23.113

Performance of Hybrid Glass Fiber-Reinforced Slag-Fly ash Blended Geopolymer Concrete

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Abstract - This study evaluates the effect of different combinations and volume fractions of hybrid glass fibers (GF) addition on the properties of slag-fly ash blended geopolymer concrete. Two types of GF (A and B) with different lengths (24 and 43 mm) were considered. GF were incorporated solely or in a hybrid combination. Three combinations of hybrid GF were used with A:B ratios of 3:1, 1:1, and 1:3 at a fixed volume fraction of 1%. Three volume fractions (0.5, 1.0, and 1.5%) were utilized with a GF hybrid combination having A:B ratio of 1:1. The performance was characterized by the workability, 1- and 7-day compressive strength, and 7-day splitting tensile strength. The experimental test results showed that the addition of GF had an adverse effect on the geopolymer concrete workability. Yet, mixes with hybrid GF were more workable than counterparts made with a single type of GF. Furthermore, the addition of hybrid GF combinations increased the compressive and splitting tensile strength by up to 26 and 59%, respectively, compared to the plain control mix. Increasing the hybrid GF volume fractions up to 1% enhanced the strengths. Superlative strengths were noted upon incorporating more long GF in the hybrid GF combination, i.e., the mix having A:B ratio of 1:3. Findings highlight the ability to improve the hardened properties of slag-fly ash blended geopolymer concrete using hybrid GF while maintaining adequate workability.

***Keywords*:** Geopolymer, concrete, glass fibers, hybrid, workability, compressive strength, splitting tensile strength.

1. Introduction

The continuous advancement in urban development is leading to extensive usage of cement-based concrete [1]. In 2020, the consumption of such concrete exceeded 3 billion metric tons and is expected to exceed 4 billion metric tons by the year 2030 [2], [3]. The production of its component, cement, has surpassed 2 billion metric tons in China, around 300 million tons in India, and around 100 million metric tons in the United States [4]. Such increasing demand for cement production for use in construction applications consumes energy and emits carbon dioxide gas. As a result, the current cement production accounts for up to 7% of the total world carbon dioxide emissions and is expected to reach 10% in the near future [5]–[8]. Among the greenhouse gases, the emitted CO_2 is trapped in the atmosphere, leading to an increase in global warming and the possibility of natural disasters, such as storms, heatwaves, floods, and droughts [9].

As an initiative to tackle such an issue, several studies have addressed the utilization of supplementary cementitious materials (SCMs) in concrete, such as fly ash, granulated blast furnace slag, silica fume, rice husk ash, and metakaolin as a replacement for cement. Yet, it was concluded that concrete with full replacement of cement that undergoes a typical hydration reaction was not possible. With alkali-activated geopolymer technology, it is possible to produce concrete with full replacement of cement using another material as a sole binder. Geopolymer binders are formulated by combining aluminosilicate materials and an alkaline activator solution. Several studies have investigated different types and combinations of aluminosilicate materials and alkaline activator solutions in forming the geopolymer binder [5], [10]–[12]. The properties of the geopolymer binder may differ depending on the characteristics of the aluminosilicate materials, the composition of the alkaline activator, and the curing condition adopted. In terms of acid and fire resistance, bond, alkali-aggregate expansion, and sulfate and corrosion resistance, geopolymers are superior to cement-based binders [3], [13]. Yet, geopolymer concrete was commonly characterized by lower resistance to cracking and high brittleness compared to cement-based counterparts [14].

To enhance its resistance to cracking and increase ductility, several studies investigated the addition of fiber reinforcement to geopolymer and cement-based concrete [15]–[19]. Steel fibers (SF) have been utilized in geopolymer concretes more frequently than other types of fibers [20]–[23]. It was concluded that the addition of SF had an adverse effect on the workability but enhanced the mechanical and durability properties. Other studies have incorporated carbon, glass, and propylene fibers in geopolymer concrete. The utilization of carbon fibers (CF) in geopolymer concrete composites enhanced the overall mechanical properties, including compressive strength, modulus of elasticity, flexural strength, impact resistance, and hardness [24], [25]. Meanwhile, the effect of glass fibers (GF) on the properties of geopolymer concrete has also been examined [26]–[29]. Lakshmi and Rao [30] reported a loss in the mechanical performance of fly ash-based geopolymer concrete upon the addition of GF beyond 3%, by volume. In another work, the addition of 0.03% GF volume fraction (v_f) in slag-fly ash blended geopolymer concrete led to superior strengths [31].

Summarizing the literature, a few studies have investigated the use of GF in geopolymer concrete. However, the effect of different combinations of micro- and macro-GFs, i.e. hybrid, and volume fraction on the workability and compressive and tensile strengths of slag-fly ash blended geopolymer concrete has not yet been investigated. Accordingly, this study aims to examine the early-age strength and workability of hybrid GF-reinforced slag-fly ash blended geopolymer concrete. Different combinations of hybrid GFs and various volume fractions of hybrid GFs were considered in this work.

2. Materials and Methods

Glass granulated blast furnace slag (referred to hereafter as slag) and class F fly ash were used as the aluminosilicate precursor binding materials in forming the geopolymer binder. An alkaline activator solution composed of grade N sodium silicate (SS) and 14 M sodium hydroxide (SH) solutions was used to activate the binder. Desert dune sand was locally sourced and used as fine aggregates. The chemical composition, particle size distribution, scanning electron microscopy, and X-ray diffraction patterns of slag, fly ash, and dune sand can be found elsewhere [7]. Their respective unit weights were 1209, 1262, and 1663 kg/m^3. The coarse aggregates used in geopolymer concrete mixes were natural dolomitic limestone with a nominal maximum size of 20 mm, dry rodded density of 1635 kg/m^3, absorption of 0.2%, abrasion mass loss of 16%, specific surface area of 2.5 cm^2/g, and specific gravity of 2.82. The natural aggregates were used in saturated surface dry condition, to avoid absorption of mixing water. Additional tap water and a polycarboxylic ether polymer-based superplasticizer were added to enhance the workability, as recommended in other work [32]. Two types of GFs were used, having two different lengths (short or long) of 24- and 43- mm, with corresponding aspect ratios of 35 and 62. The diameter, tensile strength, Young's modulus, and specific gravity of both types of GFs were similar with respective values of 0.7 mm, > 1000 MPa, 42 GPa, and 2.0. Further details on the utilized GFs can be found elsewhere [6].

3. Mixture Proportioning

Table 1 presents the mixture proportions of the geopolymer concrete mixes in this study. The benchmark mix A0B0GF0, adopted from a previous study [6], was designed to achieve a cube compressive strength (fcu) of 30 MPa and a slump of at least 150 mm. All mixes had similar proportions but different combinations and volume fractions of GFs. The binder was formed by combining slag and fly ash as a blend at a 3:1 ratio and an alkaline activator solution. Such a blend was recommended by previous work as it possessed a superior performance among others [11]. In addition, utilizing both slag and fly ash in forming the binder aimed to eliminate the heat curing associated with fly ash-based geopolymer and reduce shrinkage caused by the alkali-activated slag concrete. The alkaline activator solution was composed of sodium silicate and sodium hydroxide solution, both combined at an SS-to-SH ratio of 1.5. The sodium hydroxide solution was 14 M, as recommended in previous studies [33]. The dune sand and coarse aggregate contents remained fixed in all mixes at 725 and 1210 kg/m3, respectively. The additional water content of 75 kg/m3 and superplasticizer content of 7.5 kg/m3 (equivalent to 2.5% of binder mass), remained fixed in all mixes.

The geopolymer mixes were designed to investigate the effect of different GF lengths, hybrid GF combinations, and hybrid GF volume fractions. Two types of GF with lengths of 24 and 43 mm, namely type A (short) and B (long), respectively, were utilized. The plain control mix did not include GF and was used as a benchmark. Two mixes were reinforced with a single type of GFs, either type A (24-mm) or B (43-mm), at a constant v_f of 1.0%, by volume, to assess the effect of fiber length. A total of three mixes were reinforced with a hybrid GF combination of equal proportions (A:B = 1:1) at different volume fractions of 0.5, 1.0, and 1.5% to evaluate the effect of different volume fractions of a hybrid GF combination. To examine the impact of different hybrid GF combinations, additional two mixes were reinforced with different hybrid GF combinations of A:B ratios of 3:1 and 1:3, at a fixed v_f of 1% and were compared to the mixes made with a single type of fiber (non-hybrids) and a hybrid GF combination at A:B ratio of 1:1 and v_f of 1%. The mixes were labelled as GF*x*-A*y*B*z*, where *x* represents the GF volume fraction and *y* and *z* represent the percentage of Type A and B GF, respectively, out of the total fiber volume. For instance, GF1.0-A25B75 represents a geopolymer concrete mixture incorporating a hybrid GF combination with a 1:3 (A:B) ratio at a volume fraction of 1.0%.

Table 1: Mixture proportioning of geopolymer concrete (in kg/m^3)

Mix ID	Aluminosilicate materials		Fine aggregates	Natural coarse aggregates	Alkaline activator		SP	Water Content	GF	
	Slag	Fly ash	Dune sand		SS	SH			Proportions (A:B)	v_f (%)
GF0.0-A0B0	225	75	725	1210	99	66	7.5	75	-	0
GF1.0-A100B0	225	75	725	1210	99	66	7.5	75	1:0	1.0
GF1.0-A25B75	225	75	725	1210	99	66	7.5	75	3:1	1.0
GF1.0-A50B50	225	75	725	1210	99	66	7.5	75	1:1	1.0
GF1.0-A75B25	225	75	725	1210	99	66	7.5	75	3:1	1.0
GF0.5-A50B50	225	75	725	1210	99	66	7.5	75	1:1	0.5
GF1.5-A50B50	225	75	725	1210	99	66	7.5	75	1:1	1.5
GF1.0-A0B100	225	75	725	1210	99	66	7.5	75	0:1	1.0

4. Sample Preparation and Testing

The geopolymer concrete samples were prepared and cast under ambient laboratory conditions with a temperature of 25±2°C and relative humidity of 50±5%. Initially, the alkaline activator solution was prepared by mixing the sodium silicate and sodium hydroxide solutions and allowing the exothermic reactions to dissipate the heat. Prior to casting, the alkaline activator solution was mixed with the additional water and superplasticizer, as applicable, and gradually added to the pre-mixed dry ingredients, i.e., slag, fly ash, coarse aggregates, dune sand, and GFs. Subsequently, the freshly-prepared geopolymer concrete was cast into 100 mm cubes and 100 mm × 200 mm cylinders (diameter × height) and vibrated on a vibration table for around 10 seconds. At last, samples were wrapped in plastic to prevent solution evaporation, demoulded after 24 hours, and then left in ambient conditions until testing.

The workability of the plain and GF-reinforced slag-fly ash blended geopolymer concrete was evaluated using the slump, in accordance with ASTM C143 [34]. The early-age hardened properties were evaluated through compressive and splitting tensile strengths. The cube compressive strength was obtained at the ages of 1 and 7 days, as per BSI 12390 [35]. Nevertheless, a previously adopted correlation for predicting the cylinder compressive strength from the cube counterpart of such concrete can be utilized in estimating the cylinder compressive strength [7]. Contrarily, the splitting tensile strength was obtained at 7 days in accordance with ASTM C496 [36]. Three replicate specimens were used for each early-age mechanical test, and an average value was obtained.

6. Experimental results and discussion

6.1 Slump

Figure 1 presents the slump of plain and GF-reinforced slag-fly ash blended geopolymer concrete mixes. The plain control mix resulted in the highest workability of 160 mm. The effect of different types and combinations of GF addition on the slump of geopolymer concrete was evaluated. The inclusion of short (24 mm) and long (43 mm) GF at a constant vf of 1%, by volume, decreased the slump to 80 and 50 mm, respectively, compared to the plain concrete mix (GF0-A0B0). Apparently, increasing the GF length to 43 mm resulted in a decrease in the workability by 19% compared to the mix with short GF. Such an adverse impact by long GF is owed to the increased possibility of fiber overlap and agglomeration. Similar findings were found on GF-reinforced fly ash based-geopolymer concrete [37].

The effect of replacing short GF with long ones by 25, 50, and 75% was evaluated through mixes GF1.0-A75B25, GF1.0-A50B50, and GF1.0-A25B75, respectively. Non-hybrid mixes (GF1.0-A100B0 & GF1.0-A0B100) were used as a benchmark. Replacing short with long GF by said percentages resulted in slump values of 110, 100, and 55 mm, respectively. This shows that the slump increases when replacing up to 50% of short GF with longer ones, but increasing the replacement percentages of short GF with longer ones (75-100%) led to a subsequent decrease. As such, it can be noted that incorporating hybrid GF combinations could enhance the workability of the slag-fly ash blended geopolymer concrete as long as more short GF are present in the mix than long ones. This is owed to the reduced cross-linking ability and fiber interlocking effect of hybrid GF compared to a single type of GF. Similar findings were noticed in self-consolidating concrete reinforced with steel-glass hybrid fiber combinations [38].

The effect of different volume fractions of a hybrid combination of GFs on slag-fly ash blended geopolymer concrete was evaluated through mixes GF0.5-A50B50, GF1.0-A50B50, and GF1.5-A50B50. The inclusion of 0.5, 1.0, and 1.5% hybrid GF combination resulted in slump values of 110, 100, and 90 mm, representing a 31, 38, and 44% decrease in a slump, compared to the plain control mix. However, it seems that increasing the v_f of a hybrid GF combination did not significantly affect the workability. Furthermore, GF1.0-A75B25 and GF0.5-A50B50 resulted in similar slump values. This indicates that the effect of increasing the v_f of hybrid GF or increasing the replacement percentage of short GF by long ones had a similar impact on the workability of slag-fly ash blended geopolymer concrete.

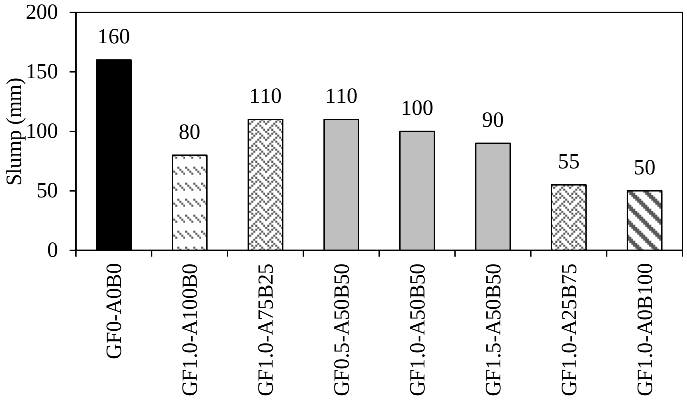


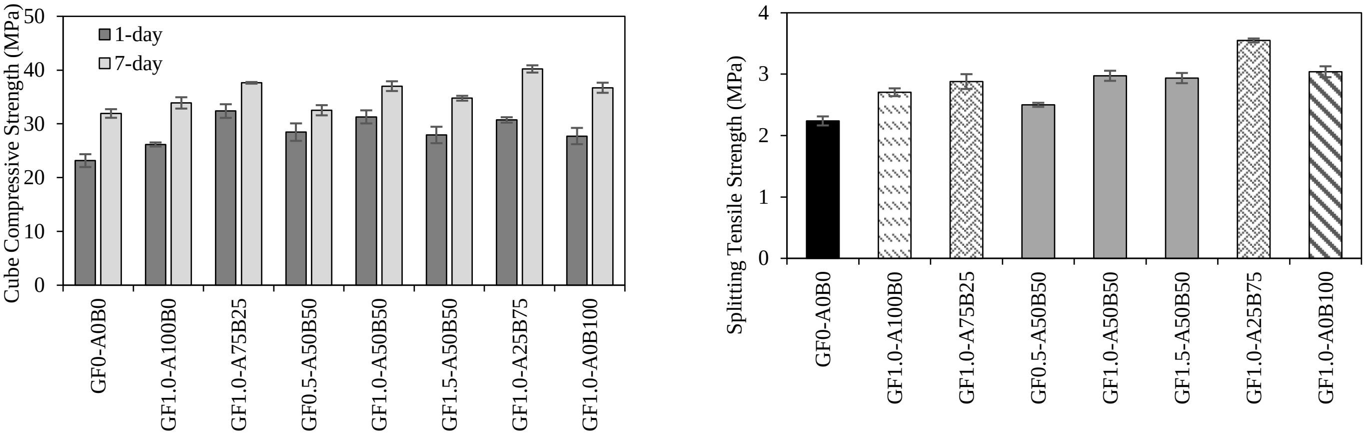
Figure 1: Slump values of geopolymer concrete mixes

6.2 Compressive Strength

Figure 2(a) presents the compressive strength (f_{cu}) of plain and GF-reinforced slag-fly ash blended geopolymer concrete. The plain control mix had a 1-day f_{cu} of 23.2 MPa. The addition of GF enhanced the 1- and 7-day compressive strengths of slag-fly ash blended geopolymer concrete. The addition of either short or long GF at 1% v_f increased the 1-day f_{cu} to 26.2 and 27.7 MPa, respectively, representing respective increases of 13 and 19% compared to the plain control mix. This shows that longer GFs were more impactful on strength than short ones. At the age of 7 days, a similar trend was noted except that the addition of long GF was more apparent. The control mix resulted in a 31.9 MPa strength. Meanwhile, the addition of short and long GFs at 1% v_f resulted in a 7-day strength of 33.9 and 36.7 MPa, respectively, representing an increase of 6 and 15% compared to the plain control mix. This strength increase from 1 to 7 days is mainly attributed to the coupled formation of calcium aluminosilicate (C-A-S-H) and calcium silicate hydrate (N-A-S-H) gels produced during the geopolymerization process within the first seven days of activation reaction [11], [19].

The effect of adding hybrid GF combinations at 1% v_f, by volume, on the 1-day f_{cu} was examined through GF1.0-A75B25, GF1.0-A50B50, and GF1.0-A25B75 mixes. These mixes were compared to their non-hybrid counterparts at a similar v_f of 1%. Replacing 25, 50, and 75% of short GF with long ones resulted in 1-day strength values of 32.4, 31.3, and 30.7 MPa, respectively, representing respective increases of 40, 35, and 32% compared to the plain control mix. This signifies further enhancement by at least 13% on the 1-day f_{cu} when incorporating a hybrid combination of GF than a single type of GF. Nevertheless, it seems like increasing the amount of long GF in a hybrid combination at 1% v_f slightly decreased the 1-day strength values. At the age of 7 days, those mixes resulted in respective increases of 62, 60, and 73% in f_{cu}, compared to the control plain mix, revealing higher strength with the presence of more long GF (Type B) in the mix. This is owed to the better bridging ability of long GF compared to that of the short ones.

The effect of incorporating hybrid GF combination at different volume fractions (0.5, 1.0, and 1.5%) was evaluated through GF0.5-A50B50, GF1.0-A50B50, and GF1.5-A50B50 mixes. Mixes incorporating 0.5, 1.0, and 1.5% of an equally proportioned hybrid GF combination had 1-day f_{cu} of 28.5, 31.3, and 27.9 MPa, respectively, and 7-day f_{cu} of 32.5, 37, and 34.8 MPa, respectively. In comparison to the control plain mix, the 1-day f_{cu} of said mixes increased by 5, 35, and 20%, correspondingly, while the 7-day f_{cu} increased by 2, 16, and 9%, respectively. Such findings highlight that hybrid GF incorporation was more impactful at 1 day. Furthermore, it is evident that at least a volume fraction of 1% of hybrid GF is needed to have an effect on the 1- and 7-day strengths with higher v_f having a more apparent impact. Thus, it can be concluded that increasing the amount of long GF in a hybrid combination or incorporating an equal proportioned hybrid GF combination at 1% v_f, by volume, would lead to an increase in f_{cu}, owing to their bridging effect and ability to defer crack formation and propagation [23], [39], [40]. It is worthy to mention that the dispersion of the test results, evidenced by the error bars in Figure 2(a), is relatively low, indicating high precision and repeatability and limited uncertainty.



(a) (b)

Figure 2: (a) Compressive and (b) splitting tensile strength of geopolymer concrete mixes

6.3 Splitting Tensile Strength

The splitting tensile strength (f_{sp}) of the 7-day slag-fly ash blended geopolymer concrete is illustrated in Figure 2(b). The plain control mix resulted in a tensile strength value of 2.24 MPa. The addition of short (Type A) or long (Type B) GF at a fixed v_f of 1% increased f_{sp} by 21 and 35%, respectively, compared to the control mix. Such an increase in f_{sp} when incorporating long GF is owed to the better bridging ability that long GF offers compared to their shorter counterparts.

The effect of different hybrid GF combinations at a fixed v_f of 1% was evaluated. Compared to the plain mix, the tensile strength increased by 29, 33, and 58% upon replacing 25, 50, and 75% of short with long GFs, respectively, indicating a significant enhancement in f_{sp} when the replacement percentage of short GF with long one increases. Furthermore, f_{sp} of these hybrid GF mixes were 6, 10, and 31% higher than those of the non-hybrid mix with short GFs (GF1.0-A100B0) and almost similar to the non-hybrid mix with long GFs (GF1.0-A100B0). This is mainly owed to the bridging effect and ability to limit the formation and propagation of micro and macro cracks upon the incorporation of GF with two different lengths.

The effect of different volume fractions of a hybrid GF combination (A:B = 1:1) on f_{sp} was evaluated. Incorporating 0.5, 1.0, and 1.5% volume fraction of hybrid GF increased f_{sp} by 12, 33, and 31%, respectively, compared to the plain control mix. Clearly, increasing v_f of hybrid GF up to 1.0% led to an increase in f_{sp}. However, beyond this volume fraction, f_{sp} was unaffected. Moreover, it can be noticed mixes including equally proportions of types A and B GF combination at 1.0-1.5% volume fractions had similar f_{sp} values to that of the mix with only long GF and greater than that of the mix with short GF, both at 1% v_f, by volume. Yet, GF1.0-A25B75 provided superior f_{sp} to all other hybrid and single GF mixes. Such observations yield that incorporating a greater amount of long GF in a hybrid combination led to superior f_{sp}. Additionally, it is clear from the error bars in Figure 2(b) that the dispersion of the test results is relatively low, indicating high precision and repeatability and marginal uncertainty.

7. Conclusions

This paper examines the effect of GF length, hybrid combination, and volume fraction on the workability and early-age strength of slag-fly ash blended geopolymer concrete. Based on the test results, the following conclusions can be drawn:

- The slump decreased upon the incorporation of GF. The incorporation of hybrid GF combinations in geopolymer concrete mixes led to better slump results than those with a single type of GFs. However, increasing the GF length in a non-hybrid combination or increasing the amount of long GF in a hybrid combination had an adverse effect on the workability. Furthermore, increasing the v_f in a hybrid GF mix decreased the slump values but to a lower extent than increasing the content of long GF.
- The addition of GF in a geopolymer concrete mix enhanced the early age compressive strength. Increasing the GF length led to greater 1- and 7-day strengths. In fact, it was noticed that the strength development between 1 and 7 days was greater when incorporating long GF solely than its counterpart mix with short GF, indicating a decrease in strength development between 1- and 7- days when incorporating short GF.
- Incorporating different hybrid GF combinations at a constant v_f of 1% led to better strengths at both ages. The strengths of mixes reinforced with hybrid GF combination surpassed their non-hybrid counterparts. Increasing the proportion of long GF in a hybrid combination further improved the strength and increased the strength development rate. The incorporation of more GF in a hybrid combination of A:B = 1:1 resulted in, on average, 35 and 10% increases in the 1- and 7-day strengths, respectively, compared to the plain mix.
- The splitting tensile strength increased upon adding GF. Increasing the length of GF or proportion of long GF in a hybrid combination increased f_{sp} of slag-fly ash blended geopolymer concrete. Furthermore, using more GF in a hybrid combination of A:B = 1:1 enhanced f_{sp} by up to 33%, respectively, compared to the plain counterpart.

Geopolymer concrete has been lately utilized in several infrastructure and structural applications, owing to its promising durability through chemical and thermal resistance. Previous applications of geopolymer concrete included but were not limited to precast pavers and slabs, railway sleepers, bricks, pre-cast pipes, and structural elements, i.e. columns, beams, tunnel segments, etc. As such, geopolymer concrete has the potential to fully replace conventional cement-based concrete in construction applications and promote sustainability. Further research is recommended to investigate the structural behavior of a hybrid-GF reinforced geopolymer concrete beams and columns.

Acknowledgements

The authors acknowledge the financial support provided by the United Arab Emirates University (UAEU) under grant number 31N453.

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