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Study on Coupling of Glass Powder and Steel Fiber as Silica Fume Replacement in Ultra-High Performance Concrete: Concrete Sleeper Admixture Case Study

Biao Li[a], Hao Li[a], Mohammad Siahkouhi[a], and Guoqing Jing[a]

[a]School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China

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ABSTRACT

To investigate the substitution of silica fume (SF) with the coupling of glass powder (GP) and steel fiber (STF), a concrete sleeper admixture (CSA) contains SF is considered as the reference concrete admixture. The use of high SF content in CSAs has negative effects on concrete rheology. Furthermore, it decreases the extensive use of ultra-high performance concrete (UHPC) in concrete markets that can mainly be caused by the limitation in available resources and the high cost of SF production. The substitution of SF with GP is insufficient; therefore, the possibility of using the coupling of GP and STF as a SF replacement has been researched. In this regard, 0.5%, 1% and 1.5% steel fiber by concrete volume and 5%, 10% and 15% glass powder and silica fume by weight of cement content have been investigated. It is found that concrete admixture with the coupling of STF and SF improves all the characteristics of the concrete. Additionally, the coupling effects of GP and STF are better than that of the SF and STF. Based on the synthetic consideration of the performance and cost, the combination of 10% GP and 1.5% STF is optimal in case of CSA mechanical performance.

1. Introduction

Annually, a large amount of concrete sleepers have been used in railway tracks. Concrete sleepers are one of the most used construction materials in the railway industry that are more paid attention, recently. Most of these sleepers due to some reasons such as overloading, environmental conditions and track stiffness are damaged and need to be replaced. Therefore, considering this much of the operational volume makes researchers have tried to find an optimal method to increase workability and decrease maintenance costs. China is one of the countries where has an extended railway network. In this case, concrete sleepers are a significant option to decrease construction cost, although, the high quality of construction is essential as well as saving budget. In the majority of sleepers, especially those are used in high-speed railway tracks, silica fume as a supplementary cementitious material has been used and decreases cement content (Zhu et al., 2018; Golafshani and Behnood, 2019; Khan and Ali, 2019). Besides advantages of using SF, negative effects can appear in concrete such as concrete rheology, the concrete production cost and concrete performance. (Wiegrink et al., 1996) in an investigation proved that high strength concretes with silica fume show higher shrinkage and their cracking develops much faster than others. (Khatri et al., 1995) concluded that 10% of cement content replaced by SF lead shrinkage of UHPC to happen at the earlier age of concrete hydration. Thus, consuming silica fume in UHPC can result in some drawbacks (Juenger and Siddique, 2015) assessed the behavior of SF and sintered SF aggregate and presented that the inhomogeneous distribution of silica fume caused swelling in some specimens. Therefore, using high amount of SF content is considered as the weaknesses of UHPCs in concrete market with respect to limited resources, high cost and negative effects on concrete performance.

Siad et al. (2017) evaluated cementitious composites with glass powder. Fly ash was replaced by glass powder to evaluate the concrete physicomechanical behavior. GP showed by 20% better performance (Siad et al., 2017). (Ramdani et al., 2019) in a research used GP coupling with rubber fibers. They showed that the coupling of rubber fiber with GP can improve the mechanical properties of concrete. Many researchers have evaluated the performance of GP in concrete. In general, GP consists of

CORRESPONDENCE Gouqing Jing gqjing@bjtu.edu.cn School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China

non-crystalline silica, sodium oxide, calcium oxide and other components. Therefore, the high amount of silicon as a basic content of pozzolanic material makes GP to be excellent for concrete industry, subsequently suitable for partial cement replacement (Vijayakumar et al., 2013; Omran and Tagnit-Hamou, 2016; Du and Tan, 2017). To understand glass powder in microstructure some investigations were performed through UHPC's behavior with GP (Vaitkevičius et al., 2014; Soliman and Tagnit-Hamou, 2017a; Soliman and Tagnit-Hamou, 2017b). (Shayan and Xu, 2006) researched that the presence of GP reduces chloride penetrability and the corrosion risk of bars embedded in concrete sleepers, especially those exist in high chloride content areas. (Kou and Xing, 2012) in an experiment, it was found out that GP in concrete decreased 7 days compressive strength, however; the replacement of cement by GP is very useful.

Moreover, it is observed that the fibers can decline the brittleness of concrete specimens and improve most of concrete properties, including tensile strength and flexural strength (Schmidt et al., 2004; Ghafari et al., 2014; Wu et al., 2016). (Ridha et al., 2017) implemented steel fiber in UHPC of a reinforced concrete corbel. Their research resulted in superior strength and deformation capacity of the concrete corbel. (Saidani et al., 2016) investigated the influence of some kinds of fibers, including steel fibers with a different shape in concrete admixtures. They found out a compelling performance of fibers in overcoming the brittle problems of concrete. (Kaïkea et al., 2014) investigated the shape of steel fibers; they showed that consumption by 2% hooked-end steel fibers in concrete decreases around 24% of the shrinkage of UHPCs.

Recent demand for better and high strength of concrete makes a development in concrete technology so that UHPC has appeared (Du and Tan, 2017). The application of UHPCs increases due to a consequent demand throughout the world (Schmidt et al., 2004). Besides, an optimal consumption of cement, superplasticizer and mineral admixtures have an important influence on UHPCs. Typical UHPC is used in concrete sleeper's admixtures contain a very high cement content, silica fume (SF), superplasticizer, fine and coarse aggregates (Kaewunruen and Meesit, 2016). Therefore, the high content of materials can lead to more cost and more disadvantages in concrete performance. In the current section tried to present researches which introduce the materials used in the current paper including drawbacks of silica fume as a common material in UHPCs.

2. Research Significance

Reviewing the studies have presented that the performance of UHPC can be improved by adding optimal amounts of GP and fibers; however, previous studies have researched independent influences of SF, GP or STF on the mechanical performance of UHPCs. Based on the authors' knowledge, no previous work has been performed on the coupling effects of GP and STF on the mechanical behavior of UHPC as SF replacement materials. Notably, in target of improving concrete sleeper's performance in two approaches of cost and workability, GP is mainly included because of its mechanical, environmental and economical significances. Therefore, GP as a filler is used to fill the gaps and improve the bond properties between the aggregates and cement paste. In addition, the fiber component also is used to improve the flexural and tensile performance of concrete and, resulting in the improved mechanical performance of concrete sleeper admixture. Some researchers have tried to replace silica fume with glass powder or another cementitious materials; however, the mechanical properties of concrete almost decreased as is proved in following sections of current research. Thus, they partially substituted silica fume. Therefore, none of them has assessed the coupling of glass powder and steel fiber as completely SF substitution materials.

Moreover, the objective of this study is to assess the properties of concrete sleeper's admixture manufactured with silica fume solitarily (15%, 10% and 5%), glass powder solitarily (15%, 10% and 5%), and both in the coupling with steel fiber (0.5%, 1% and 1.5%). In order to effectively investigate the combined use of GP and STF on the mechanical properties of UHPC, compressive strength, tensile strength, flexural strength, fresh density, workability and scanning electron microscopy (SEM) of concrete specimens are measured for 7, 28 and 56 curing days. In addition, the cost of 1 m^3 concrete for all admixtures are compared. Moreover, the fresh density of concrete is nominated as a factor for the final weight of concrete sleeper that can be effective in stabilization of railway tracks. The findings of this research can contribute to promoting the application of UHPC manufactured with steel fibers and glass powder in concrete sleepers.

3. Materials and Methods

3.1 Materials

All the materials used in this research, are the same as those are

Table 1. Chemical Composition and Physical Properties of Cementitious Materials

Item	Cementitious materials (%)		
	Cement	Silica fume	Glass powder
SiO_2	22.20	99.80	76.00
Al_2O_3	5.60	0.12	1.60
Fe_2O_3	4.50	0.09	0.42
MgO	1.60	0.20	1.21
Na_2O	_	0.21	13.00
K_2O	_	0.55	0.52
Cao	64.50	0.45	11.45
	Compounds		
C_3S	52.40	_	_
C_2S	22.50		
C_3A	6.70		
C_4AF	10.60		
	Physical properties		
Specific gravity (kg/m^3)	3,170	2,220	2,100
Specific surface (m^2/kg)	310	18,000	380
Mean particle size, d_{50}, (μm)	11.00	0.12	13.00

Table 2. Properties of Steel Fiber

Type of Fiber	Length L (mm)	Diameter D (mm)	*Aspect ratio L/D	Density (g/cm^3)	Tensile strength (N/mm^2)
Hooked-end steel (STF)	30	0.6	50	5.6	975

*Steel fiber aspect ratio: Length/Diameter (L/D)

used by concrete sleeper factory, excluding GP. Ordinary Portland Cement (II) with Table 1 physical properties was consumed in this research (Chengdu Hefeng New Material Co., Ltd., 2019). Glass powder used in this research obtained from waste glasses, this powder was bought from a factory which after gathering waste glasses and washing them, make them powder for different purposes (Foshan Yohe Chemical Technology Co., Ltd., 2019). Other materials were prepared from the concrete sleeper factory that can be sure all the materials in this research have the properties as same as those are used in concrete sleepers. All of the UHPC admixtures are designed with GP, SF as fillers coupling with STF. The glass powder material with a maximum particle size of 0.01 mm is denoted as GP. The silica content of the powder is 81%, its Na_2O content 13%, and its specific gravity 2,100 kg/m^3. Table 1 presents the chemical composition and physical properties of the cementitious materials such as GP and SF. A polycarboxylate superplasticizer with specific gravity of 1.09 and solid contents of 32% is used in all the concrete admixtures. Furthermore, steel fibers with properties according to Table 2 have been used. Hooked-end steel fiber (Fig. 1) compared to smooth one has the better workability, especially in concrete sleeper production which is proved by (Afroughsabet et al., 2019), therefore, this kind of steel fiber is chosen.

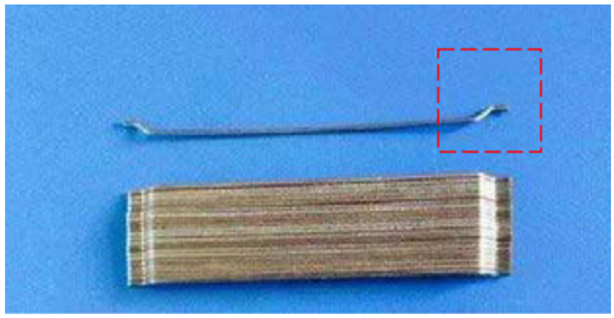

Fig. 1. Hooked-End Steel Fiber

Table 3. Mix Proportions of Concrete Admixtures

Mix No.	Mixture ID	W/C	Water	Cement	Silica fume	Glass powder	Steel fiber	Fine agg.	Coarse agg.	Cost (RMB)
			(kg/m^3)							
1	5GP-0STF	0.28	128.8	437	_	23	0	691	1229	1455
2	5GP-0.5STF	0.28	128.8	437		23	3.9	691	1229	1482
3	5GP-1STF	0.28	128.8	437		23	7.8	691	1229	1510
4	5GP-1.5STF	0.28	128.8	437		23	11.7	691	1229	1537
5	10GP-0STF	0.28	128.8	414		46	0	691	1229	2317
6	10GP-0.5STF	0.28	128.8	414		46	3.9	691	1229	2344
7	10GP-1STF	0.28	128.8	414		46	7.8	691	1229	2371
8	10GP-1.5STF	0.28	128.8	414		46	11.7	691	1229	2399
9	15GP-0STF	0.28	128.8	391		69	0	691	1229	3178
10	15GP-0.5STF	0.28	128.8	391		69	3.9	691	1229	3206
11	15GP-1STF	0.28	128.8	391		69	7.8	691	1229	3233
12	15GP-1.5STF	0.28	128.8	391		69	11.7	691	1229	3260
13	5SF-0STF	0.28	128.8	437	23	_	0	691	1229	2651
14	5SF-0.5STF	0.28	128.8	437	23		3.9	691	1229	2678
15	5SF-1STF	0.28	128.8	437	23		7.8	691	1229	2706
16	5SF-1.5STF	0.28	128.8	437	23		11.7	691	1229	2733
17	10SF-0STF	0.28	128.8	414	46		0	691	1229	4709
18	10SF-0.5STF	0.28	128.8	414	46		3.9	691	1229	4736
19	10SF-1STF	0.28	128.8	414	46		7.8	691	1229	4763
20	10SF-1.5STF	0.28	128.8	414	46		11.7	691	1229	4791
21	**RF-15SF-0STF**	**0.28**	**128.8**	**391**	**69**		**0**	**691**	**1229**	**6766**
22	15SF-0.5STF	0.28	128.8	391	69		3.9	691	1229	6794
23	15SF-1STF	0.28	128.8	391	69		7.8	691	1229	6821
24	15SF-1.5STF	0.28	128.8	391	69		11.7	691	1229	6848

3.2 Concrete Mixtures and Mixing Procedure

In the current study, the concrete sleeper admixture is considered as the reference (RF) one. Through designing the concrete admixtures, it was attempted that find a substitution method for omitting silica fume usage. Twenty four admixtures are presented in Table 3. In the RF admixture, 15% SF is used without any steel fiber; therefore, this percentage of SF decreases to 10% and 5%. On the other hand, after omitting SF, In order to obtain the optimal filler, the GP is used in UHPC admixtures to fully replace the SF content with percentages of 5%, 10% and 15% similar to SF's. To improve the mechanical properties of UHPC without SF, the coupling of GP and STF (0%, 0.5%, 1% and 1.5%) are investigated. For further assessment, the coupling of the SF and STF (the same percentages with the GP and STF coupling) also is assessed. The SEM observation is performed on many pictures of admixtures with GP and SF; subsequently, their results are reported. The workability and mechanical properties of the UHPC admixtures are considered to select the optimal one with GP and STF that can be a substitution method for admixtures with SF.

The admixture composition, material properties, and test methods are defined in the current section. To combine powder materials in concrete admixture, they were mixed before the water and superplasticizer addition, in this way, particle agglomeration could be avoided. Firstly, the fine and coarse aggregates were mixed in the mixer. Afterward, the powder materials were added to the mixer's contents and mixed for around 5 minutes. Then almost half of the superplasticizer was diluted in the admixture water and was gradually added about 4 minutes. The remaining superplasticizer was gradually added during the next 4 minutes of mixing. STFs were added in three parts, the first, middle and almost end of the mixing time. Finally, the fresh properties of the concrete admixtures as fresh density (BS EN 12350-7:2009, 2009) and slump (ASTM C185, 2015) were measured. All the mechanical experiments such as compressive, tensile and flexural strengths were performed according to Chinese national standard GB/T 50081-2002 (GB/T 50081-2002, 2002). Because the slump was very low, the shaking table was used to spread concrete through the concrete molds uniformly. The specimens without any moving were covered with plastic sheets and kept at 24ºC for a day before demolding. After demolding, the samples were cured in a basin contains water saturated by lime powder under three different curing days of 7, 28 and 56 days.

4. Results and Discussion

4.1 Density

As is shown in Fig. 3, the results of the density of fresh concrete (fresh density) is presented. The density of the specimens those which have steel fiber is higher. The highest values of the density between specimens belong to the cubes

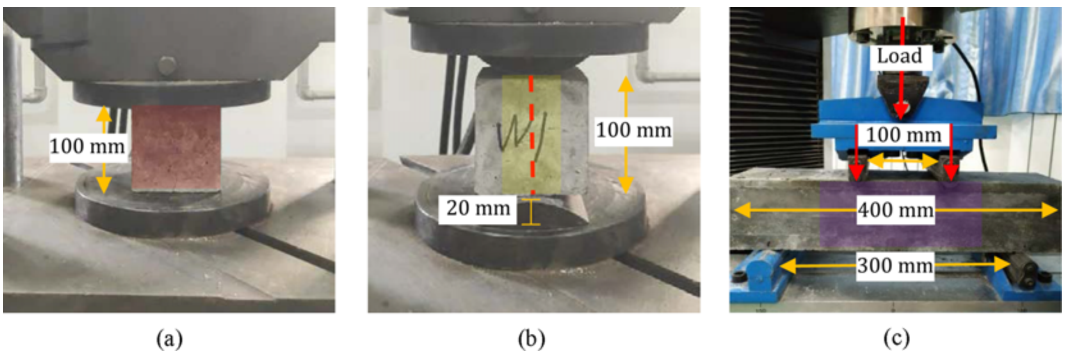

Fig. 2. Three Instruments Used in this Research for: (a) Compressive Strength, (b) Tensile Strength, (c) Flexural Strength Tests

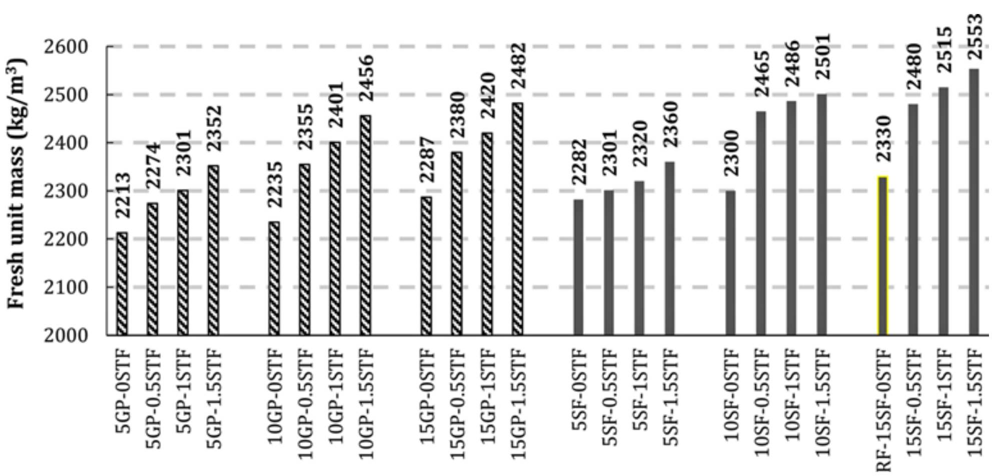

Fig. 3. Fresh Density of 24 Specimens with SF, GP and STF

that have steel fibers, due to the density value of the steel fiber which is higher than the GP and SF. The fresh density of admixtures with SF is more than those which have GP because SF has a bigger specific gravity (Table 1). The assessment of density is critical because it is nominated as the final weight of the concrete sleepers. A concrete sleeper with the same properties but heavier than others is useful in lateral resistance and stability of railway tracks. CSA with STF causes heavier sleeper thus increase concrete sleeper performance such as lateral resistance, track stability and durability, especially in railway curves (Esmaeili et al., 2016; Poulton, 2016; Jing et al., 2018). (Bezgin, 2017), in an investigation, proved that the heavier sleeper could lead to more stabilized railway tracks, especially in high-speed tracks. This factor is crucial, while many budget costs to retrieve track position and modify its elevation. Therefore, the fresh density of concrete admixture at the end of this research considered as one of evaluation factors that effect on sleeper performance.

4.2 Slump Test

Looking at the slump values of the admixtures (Fig. 5), it can be found out that slump values of concrete sleeper admixtures are low even less than 20 mm. It shows that concrete workability directly can be influenced by adding the steel fibers to concrete. With a high volume fraction of the steel fibers, the workability of the concrete largely decreases. For the same GP and SF ratio of 15% without steel fibers, the workability of admixtures with GP is more than SF, although, in the same ratio of 5% GP and SF, the workability of SF is higher. Respect to increase the percentage of GP and SF to 10%, the workability of GP admixtures increases compared to SF. When the steel fibers are added, the workability of admixtures with SF more decreases compared to those which have GP. The use of steel fibers increases the surface area of concrete ingredients and leads to decrease slump results. However, in the production of concrete sleepers regarding effective vibration methods and shaking tables, the workability of concrete cannot be that much concern of concrete sleeper producers.

Fig. 4. The Comparison of Failure Patterns in Admixtures: (a) 15SF-1STF, (b) RF-15SF-0STF in Compressive Strength Test

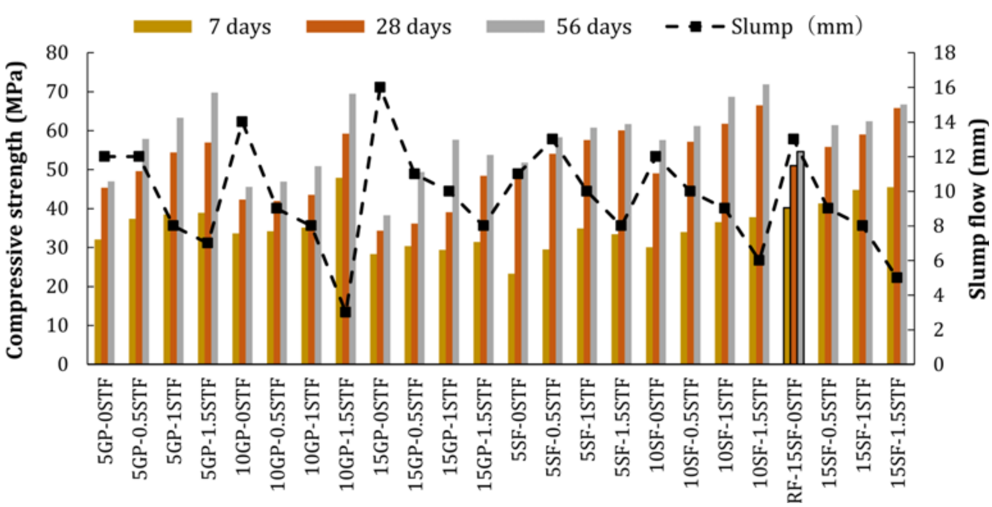

Fig. 5. Compressive Strength and Slump Test Results of Specimens in 7, 28 and 56 Days Curing

4.3 Compressive Strength Test

Cube specimens with size of 100 mm × 100 mm × 100 mm were cured for the ages of 7, 28 and 56 days before testing. As shown in Fig. 5, the compressive strength of admixture with the 10% SF and 1.5% steel fiber after 56 days has reached the highest strength observed in the tests, followed by the 5GP-1.5STF admixture, then the 10GP-1.5STF admixture and 10SF-1STF. All of the admixtures have not exceeded the RF concrete compressive strength after 56 days, such as 5GP-0STF, 10GP-0STF, 10GP-0.5STF and 15GP-0STF. The compressive strength of the RF concrete admixture compared to the concrete admixtures with GP and STF has shown almost more values, which means that the compressive strength is affected by the substitution of SF with GP and STF.

Presenting the compressive strengths of the concrete admixtures containing 5%, 10% and 15% GP after different curing ages show that just GP is ineffective substitution. The compressive strength values of RF admixture in 7, 28 and 56 days are 40.2, 51 and 54.6 MPa, that these values have reduction as the percentages of 20%, 10% and 13% for 5GP-0STF, 16%, 17% and 16% for 10GP-0STF, 30%, 32% and 30% for 15GP-0STF, respectively. As can be seen, replacing just SF with GP cannot improve the compressive strength of concrete. In addition, it means that by increasing the GP content, the compressive strength decreases. On the other hand, adding 0.5%, 1% and 1.5% of GP yields higher compressive strength values than RF admixture. The maximum compressive strength values at 7 days, 28 days and 56 days were 37.8, 66.5 and 71.9 MPa for the 10SF-1.5STF, 38.9, 57 and 69.8 MPa for the 5GP-1.5STF, 47.9, 59.2 and 69.5 MPa for 10GP-1.5STF and 36.5, 61.8 and 68.7 MPa for 10SF-1STF admixtures, respectively. The admixtures' compressive strength evaluation shows that 1.5% STF leads to the highest compressive strength value.

The compressive strengths of all the specimens are listed in Fig. 5. In order to more reliable values, the average of the test results of the three specimens are considered for each admixture. It can be seen that the addition of 1.5% STF to RF admixture causes a 22% increase in the compressive strength (56 days), whereas the completely GP (15%) replacement causes a 30% reduction in the compressive strength. The addition of 0.5% and 1% STF improve the compressive strength of 15% GP concrete by 30% and 50%, respectively. Therefore, the admixture with GP compared to Silica fume may have a disadvantage on the compressive strength of concrete, whereas the addition of STF can reduce or disappear the negative effects of GP. Fig. 4 shows the failure patterns of admixtures 15SF-1STF and RF-15SF-0STF. Destruction of concrete specimen surface in absence of steel fibers can be seen compared to admixture with steel fiber that contains some longitudinal and lateral cracks. It can be concluded that the presence of steel fiber can prevent such a defect under compressive pressure.

For admixture group with GP with STF, the incorporation of GP content (10%) and STF (1.5%) significantly improves the compressive strength, and the improvement is better than that of 15% SF. These findings indicate that the addition of 10% GP is the best choice for improving the compressive strength of concrete. For the group SF with STF, when the 1.5% and 1% STF is added, the compressive strength of concrete with 10% SF increases by 31% and 26%, respectively, in 56 days.

Regarding the performance of GP in 7, 28 and 56 curing days, it can be found out that the highest performance of this material belongs to 56 days. For instance, in 7 days curing of concrete admixtures, most of the admixtures with GP have less values of compressive strength than RF one. It shows that concrete with GP in a long period of time has better performance even better than with SF.

All in all, in case of compressive strength, the results show that the admixtures as 5GP-1.5STF, 10GP-1.5STF and 10SF-1STF have significant properties, among others. However, there are other admixtures better than RF one, but those have the lower values compared to the three above-mentioned admixtures. In the following sections, by considering other experiments' results,

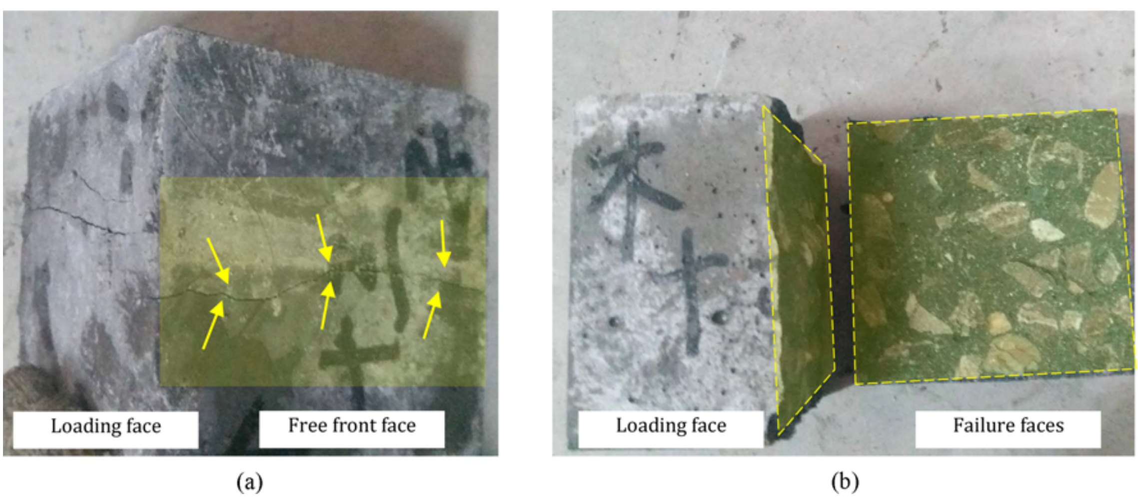

Fig. 6. The Comparison of Failure Patterns in Admixtures: (a) 15SF-1STF, (b) RF-15SF-0STF in Tensile Strength Test

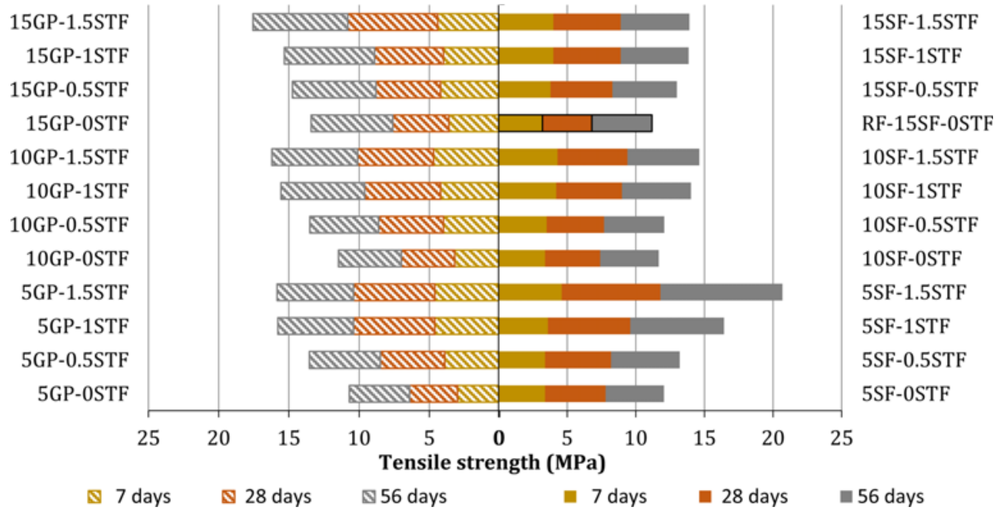

Fig. 7. Tensile Strength of Specimens in 7, 28 and 56 Days

the optimal admixture is extracted.

4.4 Tensile Strength Test

The 7, 28 and 56 days tensile strengths, obtained on similar size of compressive strength cubic specimens, are reported in Fig. 7. It has shown that the minimum values of tensile strengths belong to those which have no STF. For instance, in RF admixture by adding 0.5% STF, the tensile strength 7% increases. Furthermore, as can be seen in Fig. 6, the failure patterns of specimens after 28 curing days, the RF admixture revealed brittle and sudden failure, while the 15SF-1STF concrete admixture shows more ductile failure under loading in presence of steel fibers. The maximum values of tensile strength are in 5SF-1.5STF, 15GP-1.5STF, 5SF-1STF, 5GP-1STF, 5GP-1.5STF and 15GP-1STF admixtures, respectively. Almost all the admixtures have higher tensile strength value than reference concrete (RF-15SF-0STF). Based on the tensile strength results, it can be concluded that the presence of SF in specimens has less effect on tensile strength thus the admixtures as 5SF-0STF, 10SF-0STF and 15SF-0STF have almost the same tensile strength values. On the other hand, adding GP from 5% to 10% and 15% increases the tensile strength so that the tensile strength of 15GP-0STF admixture compared to RF admixture has almost 33% higher value. Despite the 5SF-1.5STF, entire admixtures with GP have better properties in case of tensile strength than RF admixture. The authors explained this GP performance by the best bond between GP particles and cement paste compared to SF particles. Compared to the SF concrete admixtures, the SF combined with STF decreases tensile strength at 7 days, 28 days and 56 days compared to the coupling of GP and STF in a high percentage of those (10% and 15%). This indicates that the hydration reactions are fast with the replacement of the SF by GP. At the curing ages due to the slow rate of reaction between SiO_2 from SF, which is more in SF, and $Ca(OH)_2$ from cement lead to a reduction of hydration products (C-S-H), by a decrease in the amount of C_3S and C_2S (the three are engaged with the concrete strength) in the admixtures (Ramdani et al., 2019).

Overall, the admixture with 5% GP and 1.5% STF is the best one compared to the other concrete admixtures, which is associated with a high compressive strength above 61.7 MPa at 56 days. In total, the performance of admixtures with GP and STF is better than RF admixture. This result proves that the coupling of steel fiber and glass powder becomes more effective for concrete strength. Concerning tensile strength for the admixtures in the presence of the GP and STF with respect to the RF-15SF-0STF, a significant improvement is detected. It should be mentioned that the following admixtures 5SF-1.5STF, 15GP-1.5STF, 5SF-1STF, 10GP-1.5STF and 5GP-1STF are improved by 100%, 54%, 56%, 40% and 23%, respectively, in 56 days.

4.5 Flexural Strength Test

The specimens with dimensions of 100 mm × 100 mm × 400 mm at 7, 28 and 56 days were tested. Fig. 9 describes the overall evaluation of the flexural properties of UHPCs. It can be found out that the RF admixture has less flexural value as 6.24 MPa in 56 days. The presence of silica fume and glass powder decreases the flexural strength of specimens by increasing their percentage from 5% to 10% and 15%. On the other hand, adding STF increases the flexural strength, so that the maximum value belongs to 5GP-1.5STF. It can be described based on the performance of STF that effectively contributes to bearing flexural loading. Fig. 8 shows the failure pattern of specimens 15SF-1STF and RF-15SF-0STF in presence and absence of STF, respectively. Thus the presence of STF can show more flexibility in concrete specimens and prevent sudden failure. In the case of GP usage in concrete admixtures, it can be understood that the presence of GP in concrete decreases the concrete flexural strength so that 15GP-0STF has the minimum flexural strength value in GP admixtures. As it is expected, the rising STF percentage increases the flexural strength, consequently. Among concrete admixtures, 5GP-1.5STF, 5GP-1STF, 5GP-0.5STF and 15SF-1.5STF have the highest values of flexural strength. Based on the results, adding

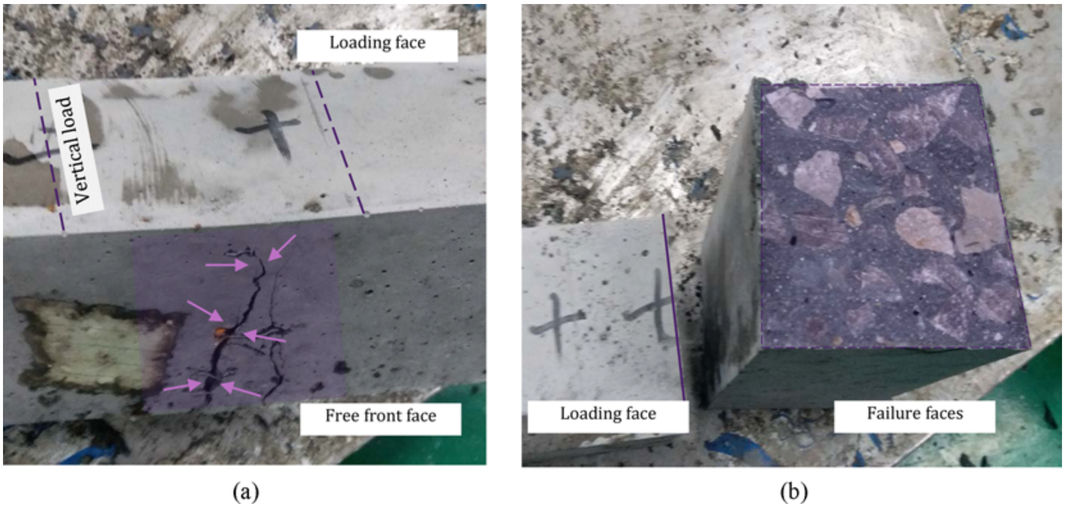

Fig. 8. The Comparison of Failure Patterns in Admixtures: (a) 15SF-1STF, (b) RF-15SF-0STF in Flexural Strength Test

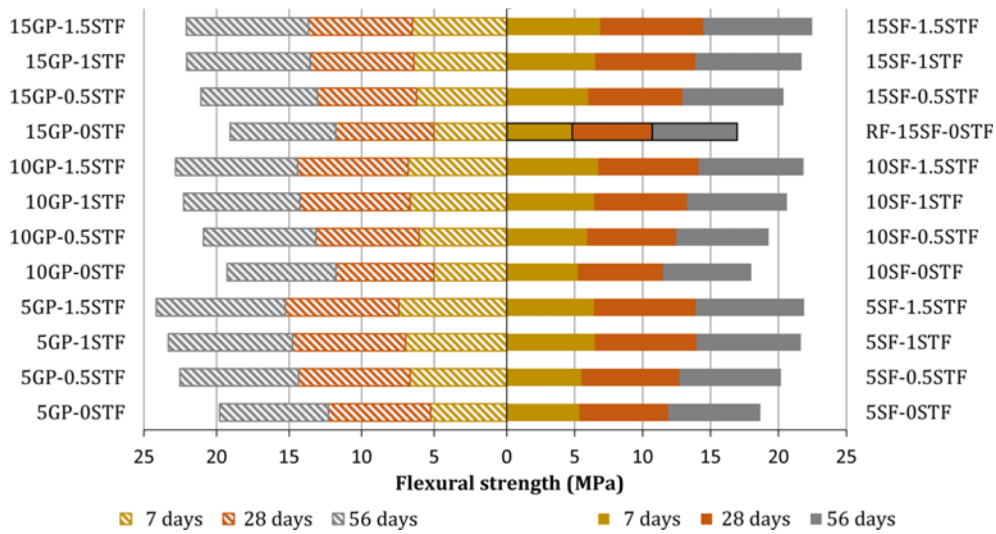

Fig. 9. Flexural Strength Test Results in 7, 28 and 56 Curing Days

the STF to the RF admixture increases the flexural strength values for 0.5%, 1% and 1.5% steel fiber as 18%, 25% and 28%, respectively. However, decreasing the amount of SF from 15% to 10% and 5%, increase the flexural strengths by 3% and 8%, respectively. Completely substitution of SF with GP by the same percentages of 15%, 10% and 5% lead to the corresponding flexural strengths for SF as 6.24 MPa, 6.48 MPa and 6.78 MPa which increase to the flexural strengths for GP as the values of 7.26 MPa, 7.49 MPa and 7.5 MPa, respectively.

Finally, the coupling of GP and STF has the best performance in case of flexural strength; therefore, based on the results, the admixtures of 5GP-1.5STF, 5GP-1STF, 5GP-0.5STF and 15SF-1.5STF can be considered as the admixtures with the highest flexural strength values.

5. Scanning Electron Microscopy Observation

To provide microscale morphology for the specimens, SEM was performed on the compressive test samples in 28 curing days. In this regard, two admixtures as 15SF-0STF and 15GP-0STF have been analyzed. To have a reliable knowledge about the microstructure, large numbers of images were collected and analyzed. Representative images are shown in Figs. 10 and 11. As shown in Fig. 10(a), the microscale morphology of SF structure is shown. Through the surface of the specimen, some width micro cracks can be seen (Fig. 10(b)). These micro cracks also cross from the SF crystals. In addition, there are some micro holes around the failure surface of specimens that can be described by the weak performance of SF and cement as paste to cover all the surface of aggregates (Fig. 10(c)). As shown in Fig. 11(a), the microscale morphology of GP crystals is presented; the pattern of GP structure can be seen. From Fig. 11(b), it can be found out that the span of the width cracks around the failure surface of this admixture is so narrower than admixture with SF. Furthermore, the micro holes exist in the specimen but with different lower depth and diameter (Fig. 11(c)). Most holes in

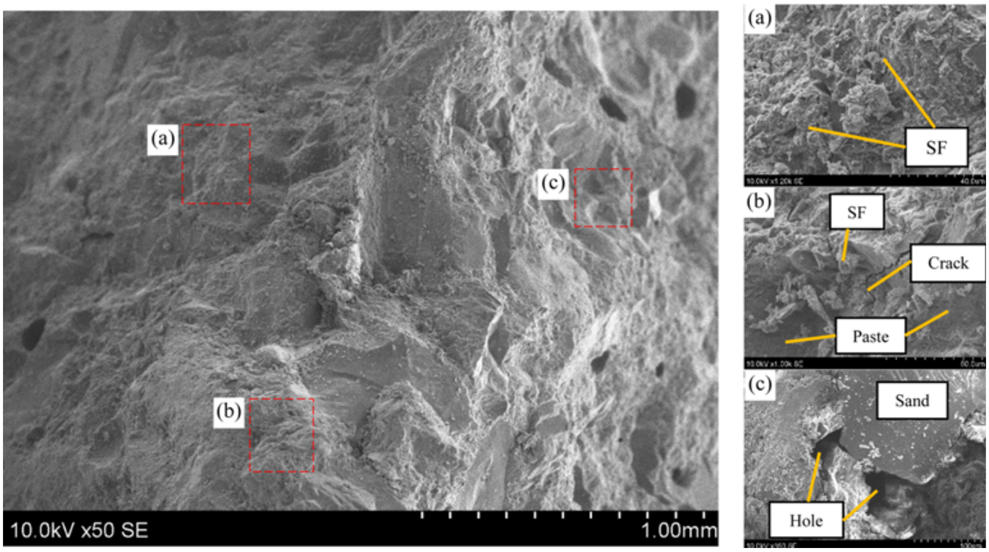

Fig. 10. Morphology of 15SF-0STF Admixture Observed under SEM: (a) Morphology of SF Structure, (b) Transverse Micro Cracks, (c) Holes

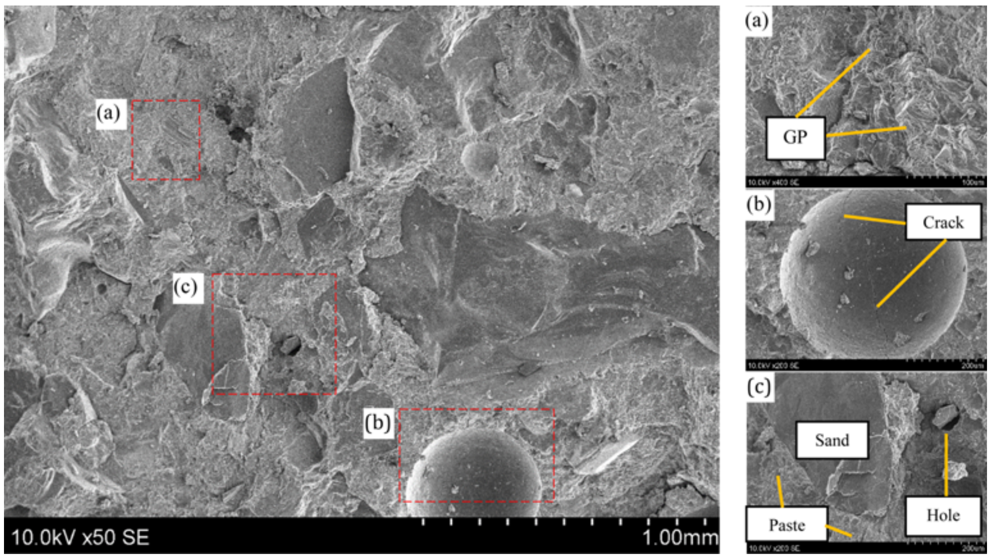

Fig. 11. Morphology of 15GP-0STF Admixture Observed under SEM: (a) Morphology of GP structure, (b) Transverse Micro Cracks, (c) Holes

15SF-0STF have a diameter smaller than 60 µm, with an average value of almost 50 µm. However, in 15GP – 0STF, the significant contribution to porosity is from holes with a diameter smaller than 40 – 50 µm. The average hole diameters is almost 45 µm.

Moreover, almost around all the aggregates are covered by the cement paste. It can be caused by the excellent performance of GP as cementitious material besides cement. Therefore the observed holes in 15SF-0STF and 15GP-0STF probably happen to one reason that the honeycomb due to the low workability of admixtures.

6. Optimal Concrete Sleeper Admixture

In order to specify optimal admixture, cost and mechanical results of 28 curing days were considered. In this regard, to select the best admixture based on cost and strength, a mathematical equation is developed to compare the alternatives and optimize the results.

Since optimization methods are based on objective functions, a multi criteria optimization method is used by a desirability function (Brandt and Marks, 1993; Bayramov et al., 2004; Mastali et al., 2018). This function calculates individual desirability function between 0 and 1 based on Eq. (1) used for mechanical results including compressive, tensile, flexural and fresh density to maximizes these values and Eq. (2) used for cost because the less amount of which is expected, respectively:

$$d_j = \left[\frac{y_j - minf_j}{maxf_j - minf_j}\right]^{t_j} \tag{1}$$

$$d_j = \left[\frac{maxf_j - y_j}{maxf_j - minf_j}\right]^{t_j} \tag{2}$$

where d_j denotes the value of desirability function of every

Table 4. Desirability Values of Admixtures

No.	Specimens	Desirability functions of					Overall desirability function
		Compressive strength	Tensile strength	Flexural strength	Fresh density	Cost	
1	5GP-0STF	0.344	0	0.584	0	1	0
2	5GP-0.5STF	0.475	0.315	0.926	0.179	0.994	0.477
3	5GP-1STF	0.624	0.631	0.978	0.258	0.989	0.629
4	5GP-1.5STF	0.704	0.631	1	0.408	0.984	0.7
5	10GP-0STF	0.248	0.105	0.438	0.064	0.840	0.228
6	10GP-0.5STF	0.239	0.315	0.625	0.417	0.835	0.439
7	10GP-1STF	0.285	0.526	0.870	0.552	0.830	0.569
8	10GP-1.5STF	0.773	0.526	0.900	0.714	0.824	0.736
9	15GP-0STF	0	0.157	0.449	0.217	0.680	0
10	15GP-0.5STF	0.059	0.315	0.481	0.491	0.675	0.312
11	15GP-1STF	0.149	0.394	0.638	0.608	0.670	0.433
12	15GP-1.5STF	0.437	0.789	0.647	0.791	0.665	0.652
13	5SF-0STF	0.425	0.263	0.321	0.202	0.778	0.355
14	5SF-0.5STF	0.614	0.368	0.661	0.258	0.773	0.495
15	5SF-1STF	0.723	0.684	0.823	0.314	0.768	0.629
16	5SF-1.5STF	0.801	1	0.824	0.432	0.763	0.737
17	10SF-0STF	0.457	0.157	0.192	0.255	0.396	0.269
18	10SF-0.5STF	0.711	0.210	0.334	0.741	0.391	0.428
19	10SF-1STF	0.854	0.368	0.476	0.802	0.386	0.541
20	10SF-1.5STF	1	0.447	0.770	0.847	0.381	0.644
21	**RF-15SF-0STF**	**0.518**	**0.052**	**0**	**0.344**	**0.015**	**0**
22	15SF-0.5STF	0.667	0.289	0.543	0.785	0.010	0.241
23	15SF-1STF	0.767	0.394	0.753	0.888	0.005	0.251
24	15SF-1.5STF	0.978	0.394	0.867	1	0	0

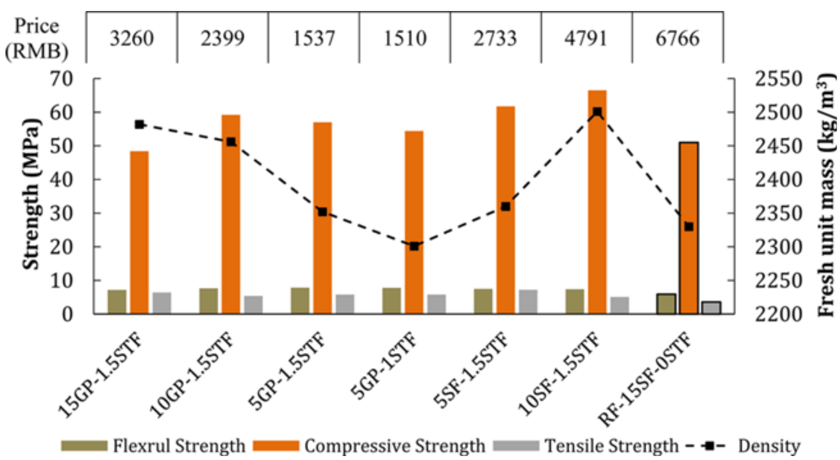

Fig. 12. Analyzing of Admixtures with Highest Performance

associated parameter, y_j is the current response of considered parameter, and min f_j and max f_j are the lowest and highest values of the *jth* response, respectively. The power value t_j is a weighting factor of the *jth* response which is considered as 1 since the independent parameters are considered to be equally important in this case (Mastali et al., 2018). Then, the objective function of current paper can be obtained by an overall desirability function (D), as shown in Eq. (3).

$$D = (d_1 \times d_2 \times d_3 \times \ldots \times d_m)^{\frac{1}{m}} \quad (3)$$

Where m is the number of the associated parameters such as mechanical properties (compressive strength, splitting tensile strength, flexural strength, fresh density) and cost of each admixture, so m in this case is 5. A higher value for an admixture's overall desirability function presents more mechanical strength and lower costs. Consequently, an optimal admixture has high values for mechanical strengths and low value for cost. The highest possible individual desirability function value for an admixture is 1, which belongs to an optimal admixture. The lowest possible individual desirability function value for an admixture is 0 that shows the worst condition.

The overall desirability functions of the admixtures were calculated; they are listed in Table 4. Specimens 5SF-1.5STF, 10GP-1.5STF, 5GP-1.5STF, 15GP-1.5STF, 10SF-1.5STF and 5GP-1STF have the highest overall desirability function values as 0.737, 0.736, 0.7, 0.652, 0.644 and 0.629, respectively. This means that the combination of GP and STF can be an efficient replacement method for both admixtures with SF and combination of SF and STF. However, 5SF-1.5STF has the highest desirability function value but it is so near to the 10GP-1.5STF admixture so that can be ignored. Finally, admixture 10GP-1.5STF is considered as the optimal one. In Fig. 12, properties of six admixtures with highest desirability function value compared to reference admixture can be seen.

7. Conclusions

The effectiveness of silica fume substitution by coupling of glass powder and steel fiber is evaluated. Therefore, the influences of 24 admixtures with coupling of 5%, 10% and 15% Glass powder with 0%, 0.5%, 1% and 1.5% steel fiber, also coupling of silica fume (0%, 10% and 15%) with the steel fiber (0%, 0.5%, 1% and 1.5%) on improving the fresh and mechanical properties of concrete sleeper admixture are evaluated. Mechanical properties of admixtures and SEM observation are performed to assess the behavior of admixtures. Finally, cost evaluation of the optimal admixture respect to the final price of 1 m^3 concrete is conducted. The study findings suggest that the coupling of glass powder and steel fiber can overcome the concrete sleeper admixture necessities in the case of concrete technology and compensate for the drawbacks of using high content silica fume in concrete admixtures. Therefore, replacing silica fume to use 10% glass powder in coupling with 1.5% steel fiber is possible to produce concrete sleepers. Based on the experimental results, the following conclusions can be drawn:

1. The production cost of 15SF-1.5STF with a price of 6848 RMB in 1 m^3 is the maximum amount compared to 5GP-0STF, which has the minimum cost amount of 1435 RMB. In total, the cost of 10GP-1.5STF with the price of 2399 RMB with respect to its mechanical properties is the optimal admixture compared to RF one and is 65% cheaper.
2. The admixtures with GP and STF have the higher fresh density value compared to RF such as 10GP-1.5STF that has 5% higher fresh density. Through compressive strength results, it is shown that the 10GP-1.5STF admixture has 10% and 22% higher strength compared to RF admixture in 28 and 56 days, respectively. Whereas the completely GP (15%) replacement causes a 30% reduction in the compressive strength without STF. The addition of 0.5% and 1% STF improves the compressive strength of 15%GP concrete by 30% and 50%, respectively.
3. The tensile strength of 10GP-1.5STF is about 15% more than the RF admixture. It can be so useful in the performance of concrete sleepers when is loaded by trains. Based on the tensile strength results can be concluded that the presence of SF in specimens has less effect on tensile strength so that the admixtures as 5SF-0STF, 10SF-0STF and 15SF-0STF have almost the same tensile strength values. On the other hand, adding GP from 5% to 10% and 15% increases the tensile strength thus the tensile strength of 15GP-0STF admixture compared to RF admixture has 33% higher value.
4. Flexural strength of 10GP-1.5STF as 8.39 MPa is by 20% more than the RF admixture with the value of 6.24 MPa. The presence of silica fume and glass powder decreases the flexural strength of specimens when their percentages from 5% to 10% and 15% are increased. However, STF increases the flexural strength.
5. Based on morphology pictures, most holes in 15SF-0STF have a diameter smaller than 60 μm, with an average value of 50 μm. However, in 15GP-0STF, the major contribution to porosity is from holes with diameter smaller than 40 – 60 μm. The average hole diameters is almost 45 μm.
6. According to defined objective function for specifying optimal admixture that can be an efficient substitution for silica fume, 10GP-1.5STF is proposed. a multi criteria optimization method is used by a desirability function associated with compressive, tensile, flexural strengths, fresh density and cost of each admixture.

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ORCID

Mohammad Siahkouhi https://orcid.org/0000-0002-4740-9503
Gouqing Jing https://orcid.org/0000-0001-9655-2229

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