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EVALUATION OF THE RELATIONSHIPS BETWEEN THE STRENGTH PROPERTIES OF HSC CONTAINING SF AND GP AT A LOW WATER-BINDER RATIO*

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Abstract– In this paper, the effect of high strength concrete (HSC) manufactured with silica fume (SF) and ground pumice (GP) is investigated. Portland cement was replaced with SF, GP and combination of SF and GP up to 25%. 22 different concrete mixtures with these replacement ratios were produced by using 0.25 water-binder ratio. The ultrasound pulse velocity, compressive, splitting tensile and flexural strengths of these concretes were determined. The experimental results show that producing HSC is feasible with SF and GP. Besides, the experimental results indicate that SF and SF in combination with GP can enhance both the short-term and the long-term properties of concrete, whereas GP needs a comparatively longer time to obtain a suitable effect. The results are also supported by scanning electron microscope analysis. The optimum replacement ratios of SF and GP are found to be 15% and 5% of cement, respectively. The relationships between ultrasound pulse velocity, compressive, splitting tensile and flexural strengths are investigated by considering the effects of SF and GP.

Keywords– Strength properties, high strength concrete, silica fume, ground pumice

1. INTRODUCTION

Recently, in civil engineering application areas, the high-performance concrete (HPC) and the high-strength concrete (HSC) have increasingly been used, as they have the benefit of decreasing the sizes of reinforced concrete frame systems that are to be used in skyscrapers. The concretes, which have compressive strength (f_c) higher than 41 MPa are generally described as HSC [1, 2] according to ACI Committee 363 [3]. Generally, HSC is obtained by using high range water reducer to decrease the water–binder ratio and by using mineral additives like metakaolin, silica fume (SF), ground granulated blast-furnace slag (GBFS), rice husk ash or fly ash so as to produce extra strength by extra calcium silicate hydrate gels formed with pozzolanic reaction [1, 4]. The developments of new chemical and mineral admixtures and very powerful superplasticizers have allowed the production of HSC [5, 6]. The general advantages of HSC improve the strength together with durability and service life of concrete constructions [2].

HPC can be planned to have the higher workability, higher finishability, higher resistance to cracking and scaling, lower permeability, higher mechanical properties and larger durability than those of conventional concrete, although it is usually produced as conventional concrete with the same Portland cement, aggregate and water in addition to chemical and/or mineral admixtures [7]. The reason for this is that the components of HPC are chosen better than conventional concrete. The use of HPC in structures is able to improve the placement without segregation between cement paste and grains of aggregate, short-

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term and long-term mechanical properties, durability, volume stability, abrasion resistance, and service life in adverse environmental conditions [8].

According to conventional concrete, HSC and HPC present many advantages. The high mechanical properties of these concretes can be utilized beneficially in construction elements such as beams, columns, precast units and shear-walls. In beams, columns and shear-walls, the decrease in the size spearheads to decrease constant weight on a structure and afterwards to decrease total weight on the base structure. These concretes can also be efficiently utilized in constructions like shell and plate. Besides, these concretes, having a very compact microstructure, probably enhance long-period durability of construction [9]. In addition, many of these concretes have been used for practices in which the adverse environmental conditions and durability were the original consideration rather than strength. For example, large span bridges, seagoing oil platforms, sea concrete constructions and submarine tunnels are such practices [10]. These concretes are also described by low porousness and revealed more uniform internal pore structure at the cement paste and aggregate particles interface than conventional concrete. Powerful interface creations increase the stiffness, strength and durability, though these concretes produced in this way generally reveal more fragile behavior [2].

The effect of SF on concrete is explained by its effect on the pore size distribution and pore construction of concrete besides its creating extra calcium silicate hydrate. SF improves the bond strength between aggregate particles and cement paste by fulfilling the interface zone more densely because of composition of ultra-fine particles. SF also performs a significant role in improvement of mechanical properties of HSC due to having a pozzolonic activity. In the concrete mixtures, filling influence of SF has a higher priority than its pozzolonic influence. The best-known influence of SF on concrete properties is the evolvement on cement paste and aggregate particles interface that are the most vulnerable areas on the concrete matrix. SF boosts the water requirement of concrete mixture when this mineral additive is used in the concrete mixture. Therefore, SF is usually used in combination with a high range water reducer to control the workability [11, 12].

In the conducted studies, pumice is usually utilized as porous aggregates. Nevertheless, very few studies have been conducted on the performance of concrete containing GP and SF in combination with GP. Demirel and Keleştemur [13] researched the influence of elevated temperature on the physical and mechanical properties of concrete obtained by replacing cement with fine GP at ratios of 5%, 10%, 15% and 20% by weight. Besides, they investigated the influence of SF (10% by weight of cement) additive on the same properties of concrete made with fine GP. They determined the ultrasound pulse velocity (U_{pv}), f_c and weight loss values on the specimens exposed to high temperature at various degrees. They reported that the f_c increased slightly up to heating at 400 ^oC and then slightly decreased between 400 and 600 ^oC. They also stated that the unit weights and the U_{pv} decreased with increasing temperature. In another study, Keleştemur and Demirel [14] investigated the corrosion behaviour of reinforcing steel embedded in concrete containing fine GP and SF on the same mixtures of their above-mentioned study. They reported that a reduction in the strength of concrete and an expansion in the corrosion rate of the reinforcing steel had occurred as a result of the fine GP. In the study of Binici et al. [15], the durability properties of concrete pipes made with GBFS and basaltic GP as fine aggregates were investigated. They observed the optimal contribution rate of pumice as 5% in the basaltic GP used at ratios of 5%, 10% and 15% by weight in place of fine aggregate. The strength and durability of alkali activated ground granulated blast-furnace slag (GGBFS) mortars with very fine GP at definite rates were investigated by Özodabaş and Yılmaz [16]. The sodium hydroxide and sodium silicate with silicate modules calculated as 0.5, 0.75 and 1.00 were used as alkaline activators for this study. The GGBFS was utilized at ratios of 60% and 80% by weight in place of cement, and in the second stage, GP was added at ratios of 5% and 10% by weight in place of GGBFS for this study. The flexural strength (f_{fs}) and f_c values of the produced concrete at 7, 28 and 90 days were investigated in their study. The f_{fs} and f_c values of the GGBFS and GGBFS in combination with very fine GP specimens were close to each other. Sarıdemir [17] researched the effect of SF and GP on the f_c and modulus of elasticity of HSC. Specifically, the study recommended that 15% weight of SF and 15% weight of SF together with 5% weight of GP can be utilized as replacement of cement so as to obtain HSC with good f_c and modulus of elasticity. In addition, the study reported that the f_c of concrete mixture containing 10% GP was higher than the f_c and modulus of elasticity of control concrete mixtures at 28 days. Binici et al. [18] investigated the mechanical and radioactivity shielding performances of mortars produced with barite, colemanite, GP and GGBFS. They prepared five groups of mortar specimens for experimental study. They reported that the later age f_{fs} and f_c of the mortars enhanced meaningfully by using GGBFS. Besides, they reported that the f_{fs} and f_c were lower than the control mortar values for all the specimens with different supplement rates of barite and pumice for all the test periods.

The main objective of this paper is to evaluate the effect of SF, GP and SF in combination with GP on the long-term and short-term strength properties of HSC. There are three series of experiments in this research. The effect of SF as artificial mineral admixture and GP as natural mineral admixture on the properties of HSC was separately investigated in the first and second series while the combined effect of these on the properties of HSC were investigated in the third series. The properties of HSC, in terms of fresh concrete slump, ultrasound pulse velocity (U_{pv}), compressive strength (f_c), splitting tensile strength (f_{sts}), and flexural strength (f_{fs}) values, were determined by using these series. In addition, the experimental results were evaluated statistically through regression analyses. The linear and power regression models were proposed to evaluate the U_{pv}, f_c, f_{sts} and f_{fs}.

2. EXPERIMENTAL PROGRAM

a) Materials

The CEM-I 42.5R ordinary Portland cement was utilized in the present paper. According to TS EN 197-1 [19], the mean f_c of this cement is higher than 42.5 MPa at 28 days. Initial and final setting times of the used cement were calculated as 130 and 215 minutes, respectively. SF and GP used in this study were provided from Antalya Electro Metallurgy Enterprise and Nevşehir Mikromin in Turkey, respectively. The chemical analysis and specific gravities of the Portland cement, SF and GP are given in Table 1. Both natural river sand (NRS) and natural crushed limestone-I (CL-I) with particles ranging from 0-5 mm in size were used as the fine aggregates. The natural crushed limestone-II (CL-II) and natural crushed limestone-III (CL-III) with sizes 5-12 mm and 5-22 mm were used as the coarse aggregates. These aggregates had specific gravities of 2.48, 2.54, 2.70 and 2.72, and mixing ratios of 25, 25, 10 and 40, respectively. Polycarboxylate type superplasticizer (SP) called as Glenium 51 (BASF Construction Chemicals Company) was used as chemical admixture. Glenium 51 is a new generation chemical admixture of copolymer based on superplasticizers.

Table 1. Chemical composition of cement and mineral admixtures

Bulk oxide	PC	SF	GP
SiO_2	21.20	85.98	71.80
Al_2O_3	5.90	0.65	12.40
Fe_2O_3	2.10	0.32	1.05
CaO	62.10	0.70	1.10
MgO	2.30	4.91	0.34
SO_3	3.40	0.63	0.08
K_2O	0.80	-	4.51
Na_2O	0.40	-	5.20
LOI*	1.80	2.66	3.52
Specific gravity	3.08	2.30	2.33

PC= Portland cement, SF= Silica fume, GP= Ground pumice, *LOI= Loss on ignition (%)

ASTM C618 [20] exhibits the physical and chemical properties for natural pozzolans to replace cement. There are two basic significant criteria for pozzolanic activity according to this standard. The first criteria is the sum of chemical ingredients (SiO_2+Fe_2O_3+Al_2O_3) and the second criteria is the strength activity index, specified as the ratio of the f_c for a mortar with 20% pozzolan to replace cement by mass to the f_c of the control mortar. As shown in Table 1, the fine SF and GP fulfill the requirements of ASTM C618 [20].

b) Specimen preparation and curing

In the present paper, three series of concrete mixtures, which are separate from the control mixture, were produced at the water-binder ratio of 0.25. The total cementitious ingredients and water used in these mixtures were kept constant at 450 and 112.5 kg/m^3, respectively. The mixture proportions of HSC containing different percentages of SF, GP and SF in combination with GP are presented in Table 2. A total of 22 HSC mixtures were tested in this study, including five mixtures (first series) containing SF named as A5, A10, A15, A20 and A25, five mixtures (second series) containing GP named as N5, N10, N15, N20 and N25, eleven mixtures (third series) containing SF in combination with GP named as A2.5+N2.5, A5+N5, A5+N10, A5+N15, A5+N20, A10+N5, A10+N10, A10+N15, A15+N5, A15+N10 and A20+N5, and one control mixture (named as C) containing no supplementary cementitious material. The specimen names and abbreviations are presented in Table 2. The concrete mixtures were produced to have slump values of 140±20 mm for the ease of workability, pumpability and finishability. During mixing process, a high range water reducing admixture was added to achieve the specified slump.

Table 2. Mixtures proportions for 1 m^3 of concrete (kg/m^3)

Mixtures No	Meaning	Cement	SF	GP	Sand	CL-I	CL-II	CL-III	SP
			%	%	(0-5 mm)	(0-5mm)	(5-12 mm)	(5-22 mm)	%
C	Control concrete	450.0	0		450.37	461.26	196.13	790.32	4
A5	5% SF	427.5	5		448.83	459.69	195.46	787.62	4
A10	10% SF	405.0	10		447.29	458.12	194.79	784.93	3.5
A15	15% SF	382.5	15		445.76	456.54	194.12	782.23	3.5
A20	20% SF	360.0	20		444.22	454.97	193.45	779.54	3
A25	25% SF	337.5	25		442.69	453.40	192.78	776.84	3
N5	5% GP	427.5		5	448.83	459.69	195.46	787.62	4
N10	10% GP	405.0		10	447.29	458.12	194.79	784.93	4
N15	15% GP	382.5		15	445.76	456.54	194.12	782.23	4
N20	20% GP	360.0		20	444.22	454.97	193.45	779.54	3.5
N25	25% GP	337.5		25	442.69	453.40	192.78	776.84	3.5
A2.5+N2.5	2.5% SP and 2.5% GP	427.5	2.5	2.5	448.83	459.69	195.46	787.62	4
A5+N5	5% SP and 5% GP	405.0	5	5	447.29	458.12	194.79	784.93	4
A5+N10	5% SP and 10% GP	382.5	5	10	445.76	456.54	194.12	782.23	4
A5+N15	5% SP and 15% GP	360.0	5	15	444.22	454.97	193.45	779.54	3.5
A5+N20	5% SP and 20% GP	337.5	5	20	442.69	453.40	192.78	776.84	3.5
A10+N5	10% SP and 5% GP	382.5	10	5	445.76	456.54	194.12	782.23	3
A10+N10	10% SP and 10% GP	360.0	10	10	444.22	454.97	193.45	779.54	2.5
A10+N15	10% SP and 15% GP	337.5	10	15	442.69	453.40	192.78	776.84	2.5
A15+N5	15% SP and 5% GP	360.0	15	5	444.22	454.97	193.45	779.54	2.5
A15+N10	15% SP and 10% GP	337.5	15	10	442.69	453.40	192.78	776.84	2.5
A20+N5	20% SP and 5% GP	337.5	20	5	448.83	459.69	195.46	787.62	2.5

A=Silica fume, N=Ground pumice, A+N=Silica fume+Ground pumice, SP= Superplasticizer, CL=Crushed limestone

All of the materials used to produce concrete were admixed in accordance with ASTM C192 [21] in a power driven turning pan-type mixer. For the prepared concrete mixtures, fifteen 100x100x100 mm cubes f_c and U_{pv} at 7, 28, 56, 91 and 365 days, three 150x150x150 mm cubes f_{sts} at 28 days, three 100x100x400 mm prisms f_{fs} at 28 days were moulded and compacted by a vibrating table. After moulding and surface finishing, all of the specimens were taken to laboratory for 24 hours. Afterwards, the concrete specimens were demoulded and moved to saturated lime water at 23±2 ^{o}C for curing until the testing age. The concrete specimens were cured according to ASTM C 192 [21].

c) Experiment procedure

After producing concrete, the workability of fresh concrete was determined in connection with slump. The slump experiment was conducted according to TS EN 12350-2 [22] and ASTM C143 [23]. The U_{pv} values of concrete were measured on 100x100x100 mm cube specimens which were produced for obtained f_c values at the ages of 7, 28, 56, 91 and 365 days. The f_c values of the concrete were determined by crushing three 100x100x100 mm cube specimens at the ages of 7, 28, 56, 91 and 365 days for each mixture. The f_c experiment was carried out by a 3000-kN capacity testing machine according to TS EN 12390-3 [24] and ASTM C 39 [25]. The f_{sts} and f_{fs} values of the concrete were determined by crushing three 150x150x150 mm cube specimens and three 100x100x400 mm prism specimens at the age of 28 days for each mixture, respectively. The f_{sts} and f_{fs} experiments were carried out according to TS EN 12390-6 [26] and TS EN 12390-5 [27].

The U_{pv} experiment is carried out by a non-destructive ultrasound testing utility. The U_{pv} is calculated by using the following Eq. (1) depending on transition time from sample size of ultrasound waves.

$$U_{pv} = \frac{S}{t} \times 10 \tag{1}$$

where, U_{pv} is the ultrasound pulse velocity (km/s), S is the length of the straight wave path through the example (cm) (10 cm in this paper), and t is the travel time of the ultrasonic pulse through S (μs).

3. RESULTS AND DISCUSSION

a) Ultrasound pulse velocity

The ultrasound pulse velocity (U_{pv}) experiment results fundamentally include the measurements of electronic wave velocity through concrete specimen. The U_{pv} experiment is used to determine the concrete quality [28]. The obtained U_{pv} values of HSC concrete containing SF, GP and SF in combination with GP at the ages of 7, 28, 56, 91 and 365 days in this study are shown in Fig. 1. In the first series, it was proved that concrete mixtures produced with SF exhibited higher U_{pv} than control concrete at all ages as seen in Fig. 1. In this series, it was observed that the best combination for improving U_{pv} was the concrete mixture with A10 and A15. This shows that the concrete with lower ingredient of SF (A5, A10 and A15) is denser than the concrete with higher ingredient of SF (A20 and A25) at the same water-binder ratio. In the second series, it can be shown from Fig. 1 that the U_{pv} values of concrete containing GP (apart from concrete containing N5) are lower than the U_{pv} of corresponding control concrete at all ages. In this series, the addition of N5 gives the best result when compared to other GP replacement levels. In the third series, SF and GP combinations increased the U_{pv} values at all ages according to the control mixture as seen in Fig. 1. It was observed that the best combination in this series for improving U_{pv} was the mixture with A15+N5. The highest U_{pv} values of specimens were found in the concrete mixtures that included A15 according to the U_{pv} value of all series. The increase in the U_{pv} values with ingredients of SF and GP in concrete reveals that the concrete quality in terms of density, uniformity and devoid of flaws is excellent.

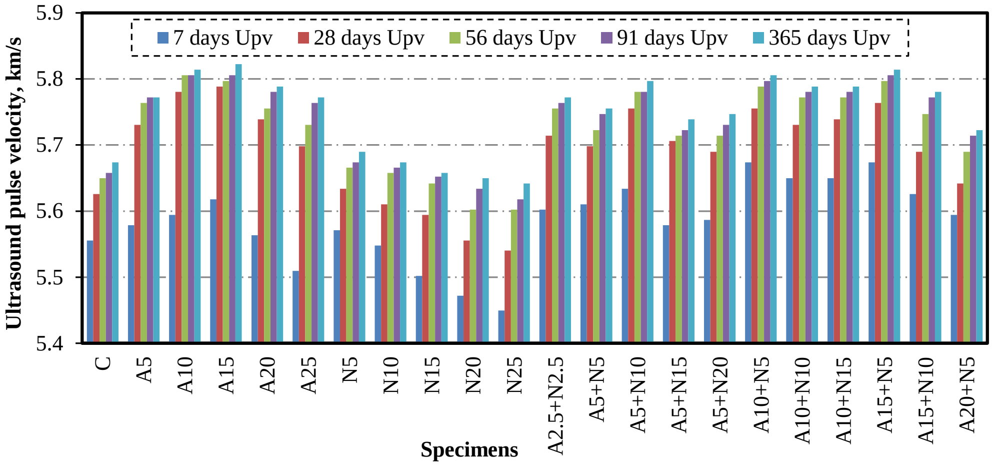


Fig. 1. The U_{pv} values of HSC containing SF, GP and SF in combination with GP

b) Compressive strength

The compressive strength (f_c) experiment results of HSC containing SF, GP and SF in combination with GP are shown in Fig. 2, where each value was averaged from the results of three 100x100x100 mm cube specimens at the ages of 7, 28, 56, 91 and 365 days. In addition, the f_c values of HSC containing SF, GP and SF in combination with GP, which are normalized according to control concrete specimens, are given in Table 3. The effect of SF, GP and SF in combination with GP on f_c values of concrete can obviously be seen from this table and figure. The results of the first series indicate that the f_c values increased with the increasing SF ingredient according to control concretes at all ages. The concrete with higher ingredient of SF (A20 and A25) revealed lower f_c values compared to the concrete with lower ingredient of SF (A10 and A15). In this series, the addition of A15 gave the best results when compared to other SF replacement levels. Shannag [29] made similar observations, indicating that the f_c of HSC concrete containing SF increased with SF ingredient up to 15% and then decreased slowly. In the second series, the f_c values (apart from concrete containing N5) were observed to have been lower than the f_c values of control concretes at all ages. In this series, the addition of N5 gave the best results when compared to the other GP replacement levels. The concrete mixtures of this series with replacement of N20 and N25 gave the lowest f_c values and were approximately between 73-90 MPa and 71-89 MPa at all ages, respectively. The contribution of GP to f_c values became more pronounced at later ages according to the early ages, because of the lower activity of GP. In these series, the f_c values were found to be between 81-122 MPa for the concretes containing SF, while the f_c values were found approximately between 71-90 MPa for the concretes containing GP, at all ages. Binici et al. [15] observed that the f_c of concrete containing GP specimens was almost equal to the f_c of the control concrete specimens. In the third series, SF and GP combinations increased the f_c values according to control concretes at all ages as seen in Fig. 2. Among the combinations in this series, it was understood that the best combination for increasing f_c values was the mixture with A15+N5. For the best combination of this series, the f_c values were found approximately between 90-119 MPa, at all ages. This means that the increase ratio of f_c values for this series is about 26% compared to the control concretes at all ages. The results of the whole series indicate that at the early ages, the SF contributed better to the f_c development of high performance cement pastes than the GP. This phenomenon was attributed to the higher rate of hydration in the concrete containing SF. The results of this paper show that the concrete mixture containing A15, N5 and A15+N5 might be considered as an optimum concrete mixture for manufacturing high to the HSC. The increase in the f_c of concretes containing SF and GP can be clarified in a way similar to the f_c increase in the mortar mixtures. Moreover, these pozzolanic materials play an important role in enhancing the cement paste and aggregate particle bond through the formation of more calcium silicate hydrate (C-S-H) ($CaO.SiO_2.H_2O$) and the density of the transition zone [29].

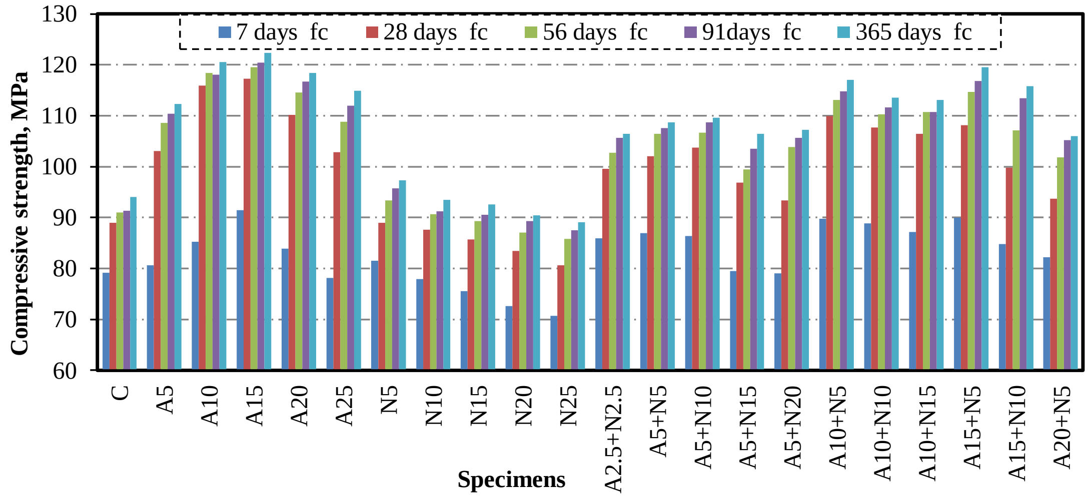


Fig. 2. The f_c values of HSC containing SF, GP and SF in combination with GP

Table 3. The normalized values of the f_c, f_{sts} and f_{fs} of HSC

Mixtures	f_c (MPa)					f_{sts} (MPa)	f_{fs} (MPa)
	7 days	28 days	56 days	91 days	365 days	28 days	28 days
C	1.00	1.00	1.00	1.00	1.00	1.00	1.00
A5	1.02	1.16	1.19	1.21	1.19	1.08	1.12
A10	1.08	1.30	1.30	1.29	1.28	1.09	1.16
A15	1.15	1.32	1.31	1.32	1.30	1.11	1.17
A20	1.06	1.24	1.26	1.28	1.26	1.10	1.12
A25	0.99	1.16	1.20	1.23	1.22	1.04	1.06
N5	1.03	1.00	1.03	1.05	1.03	1.02	1.02
N10	0.98	0.98	1.00	1.00	0.99	1.00	1.00
N15	0.95	0.96	0.98	0.99	0.98	0.99	0.99
N20	0.92	0.94	0.96	0.98	0.96	0.97	0.98
N25	0.89	0.91	0.94	0.96	0.95	0.95	0.96
A2.5+N2.5	1.09	1.12	1.13	1.16	1.13	1.05	1.05
A5+N5	1.10	1.15	1.17	1.18	1.16	1.05	1.06
A5+N10	1.09	1.17	1.17	1.19	1.17	1.06	1.08
A5+N15	1.00	1.09	1.09	1.13	1.13	1.02	1.02
A5+N20	1.00	1.05	1.14	1.16	1.14	1.00	1.00
A10+N5	1.13	1.24	1.24	1.26	1.24	1.09	1.13
A10+N10	1.12	1.21	1.21	1.22	1.21	1.07	1.09
A10+N15	1.10	1.20	1.22	1.21	1.20	1.07	1.05
A15+N5	1.14	1.22	1.26	1.28	1.27	1.08	1.09
A15+N10	1.07	1.12	1.18	1.24	1.23	1.05	1.03
A20+N5	1.04	1.05	1.12	1.15	1.13	1.00	0.99

f_c= Compressive strength, f_{sts}= Splitting tensile strength, f_{fs}= Flexural strength

c) Splitting tensile strength

The splitting tensile strength (f_{sts}) experiment results of HSC containing SF, GP and SF in combination with GP are shown in Fig. 3, where each value was averaged from the results of three 150x150x150 mm cube specimens at the age of 28 days. In addition, the f_{sts} values of these concretes, which are normalized according to the f_{sts} value of control concrete, are given in Table 3. The variation of f_{sts} values for all specimens is similar to that of the f_c. In the first series, it can be observed that the concretes produced with SF show higher f_{sts} than control concrete at 28 days as seen in Fig. 3. The increases in the f_{sts} values according to control mixture for this series were determined as approximately 8%, 10%, 11%, 10% and 4% for A5, A10, A15, A20 and A25 ingredients, respectively. In this series, it was observed that the best combination for improving f_{sts} was the concrete mixture with A15. A similar result was observed in the study by Güneyisi et al. [12] and Shannag [29]. Besides, Almusallam et al. [30] and Bhanja and Sengupta [31] investigated the effect of SF on the f_{sts} of HPC. They stated that the highest f_{sts} was observed in the 15% SF ingredient concretes followed by those produced with 10% SF ingredient. In the second series, the f_{sts} of concrete mixtures containing N5 and N10 were higher than the f_{sts} of control concrete at 28 days, while the f_{sts} of concrete mixtures containing N15, N20 and N25 were lower than the f_{sts} of control concrete at 28 days. In this series, the increases in the f_{sts} values according to control mixture were determined as approximately 2% and 0.2% for N5 and N10 ingredients, respectively, while the decreases were determined as approximately 1%, 3% and 5% for N15, N20 and N25 ingredients, respectively. In this series, it is observed that GP ingredient was not so effective on the f_{sts} values. In the third series, SF and GP combinations increased the f_{sts} values at 28 days according to control concrete. In this series, it was observed that the best combination among these tried combinations for improving f_{sts} values was the mixture with A10+N5. The addition of more than 20% SF and GP replacement with cement decreased the f_{sts} values. The replacement of SF by weight of cement up to 20% (A5, A10, A15 and A20) in concretes containing GP up to 10% (N5 and N10) has enhanced the f_{sts} of the concretes and lifted them above that of the control concrete. In the literature, there are no studies on the f_{sts} values of concrete containing GP and SF in combination with GP.

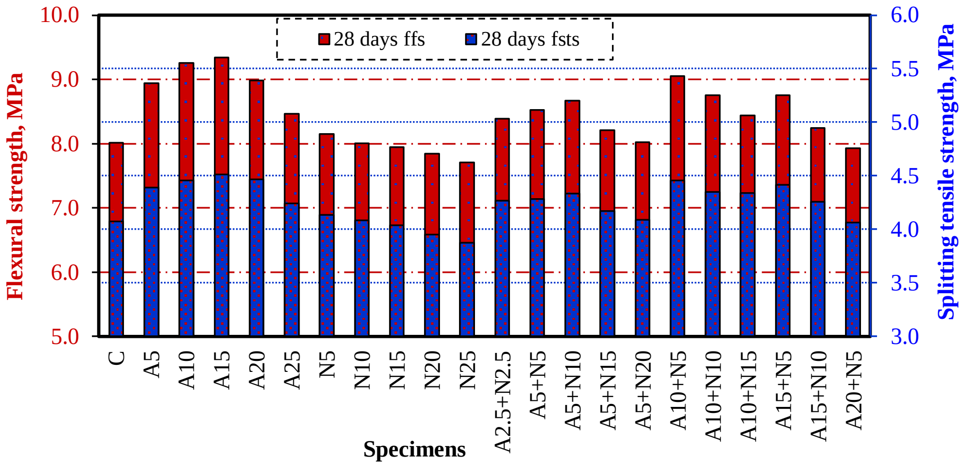


Fig. 3. The f_{sts} and f_{fs} values of HSC containing SF, GP and SF in combination with GP

d) Flexural strength

The experimental results of flexural strength (f_{fs}) of HSC containing SF, GP and SF in combination with GP at the age of 28 days are exhibited in Fig. 3. Each value in this figure represents the average f_{fs} values of three 100x100x400 mm prism specimens. Besides, the f_{fs} values of these concretes, which are normalized according to the f_{fs} value of control concrete, are given in Table 3. In the first series, it can be observed that concretes containing SF show higher f_{fs} than control concrete at 28 days as seen in Fig. 3. From the experimental results of this series, it can be seen that there is increase in f_{fs} with replacement in the range of A5, A10 and A15 of cement by SF; nevertheless, the rate of increase of f_{fs} reduces with replacement within the range of A20 and A25 of cement by SF. In this series, it was observed that the best combination for improving f_{fs} was the concrete mixture with 15% SF like other strength properties. Bhanja and Sengupta [31] investigated the contribution of SF on the f_{fs} of HPC. Studies carried out by various researchers stated that the gains in f_{sts} values were higher than the f_{fs} values at lower replacement levels.

They found that the optimum replacement ratios of SF were about 15% to 25% of cement. In the second series, the f_{fs} values increase with replacement in the range of A5 of cement by GP, while the f_{fs} values decrease with replacement in the range of A10, A15, A20 and A25 of cement by GP. In this series, the increase in the f_{fs} value according to control mixture was determined as approximately 2% for A5 ingredients, while the decrease was determined as approximately 0.1%, 1%, 2% and 4% for A10, A15, A20 and A25 ingredients, respectively. In the third series, SF and GP combinations increase the f_{sts} at 28 days according to control concrete separate from concrete containing A20+N5, and A5+N20. In this series, it was observed that the best combination among these investigated combinations for improving f_{fs} was the mixture with replacement in the range of A10 and N5. The study shows that the addition of more than 20% of SF and GP combination replacement with cement decreases the f_{fs}, similar to the f_{sts}.

e) Microstructure analysis

Microstructure analysis was carried out by scanning electron microscopy (SEM) to identify the porosity and morphology of the interface transition zone between the aggregate and cementitious materials. The microstructure analysis was made with concrete specimens of the control concrete, the concrete containing A15, the concrete containing N5 and the concrete containing A15+N5. The morphology of interface transition zone was carried out on the small samples taken from the randomly broken concrete specimens.

Figure 4 reveals the effect of SF, GP and SF in combination with GP on morphology of the interface transition zone for the specimens obtained from the highest strength properties from all series. As shown in Fig. 4, with addition of SF, GP and SF in combination with GP, the make-up of the interface transition zone improves. Particularly, the C-S-H gels form the majority of the hydration products and the component of calcium hydroxide reduces because of pozzolonic influences. As shown in Fig. 4, the amount of hydration products obtained from the concrete containing A15 and A15+N5 is higher compared to those of control concrete and the concrete containing N5. It can be deduced that strength of concrete containing GP is comparatively low, since pozzolanic activity of GP is not as good as pozzolanic activity of SF. This is one of the most significant factors on the strength increase. Moreover, the fineness of SF and GP is a significant parameter with regard to filling gaps between aggregate and cement. Particularly, the average particle size of SF used in the concrete mixtures is very small compared to that of cement and GP. Therefore, the microfiller influence of SF may be as significant as the pozzolanic influence of SF at the strength increase [14, 32].

4. ANALYSIS OF EXPERIMENTAL RESULTS

The regression analysis is modelled by linear and power regression equations for evaluating the relationship between independent and dependent variables. The general forms of the linear and power regression models can be defined as follows, respectively:

$$y= a+bx \tag{2}$$

$$y= ax^{b} \tag{3}$$

where y, a, b and x are the dependent variable, constant coefficients and the independent variable of the problem dealt with, respectively.

In the present paper, the relationships between cube f_c, U_{pv}, f_{sts} and f_{fs} values of HSC containing SF, GP and SF in combination with GP obtained from experimental study were investigated with linear and power regression models.

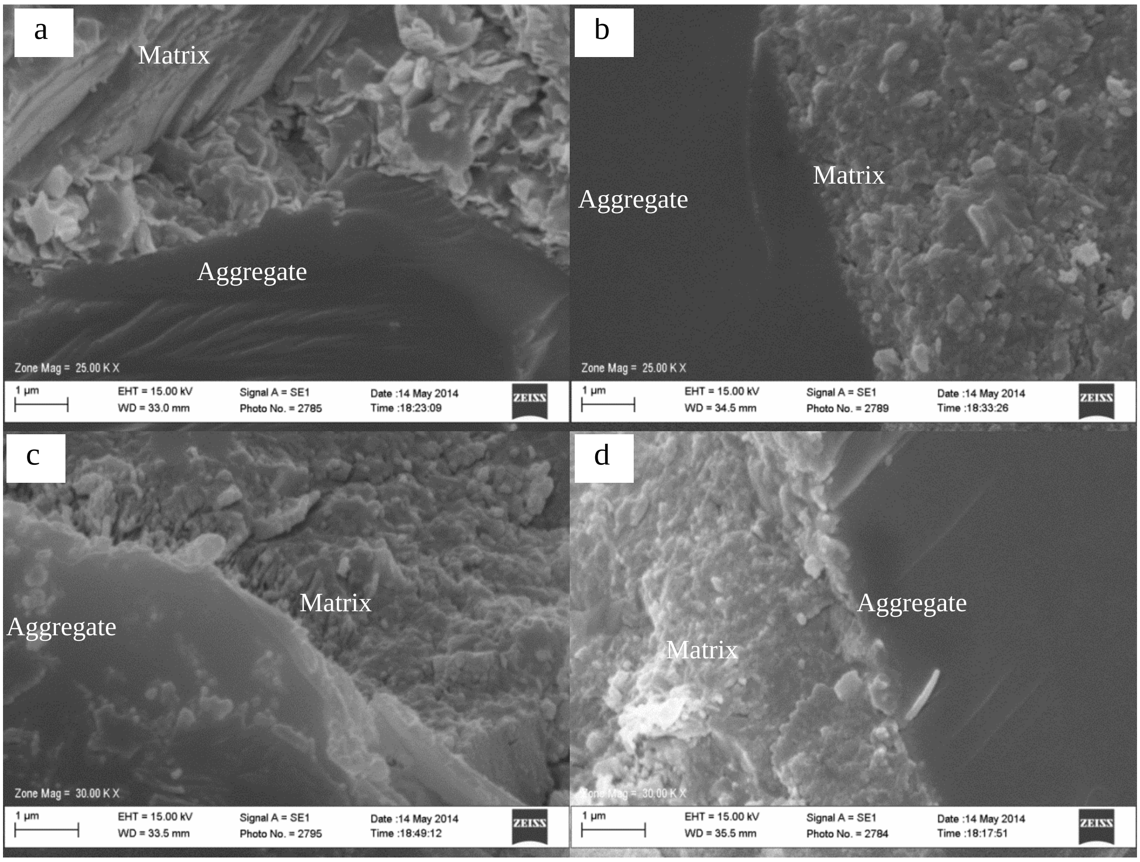


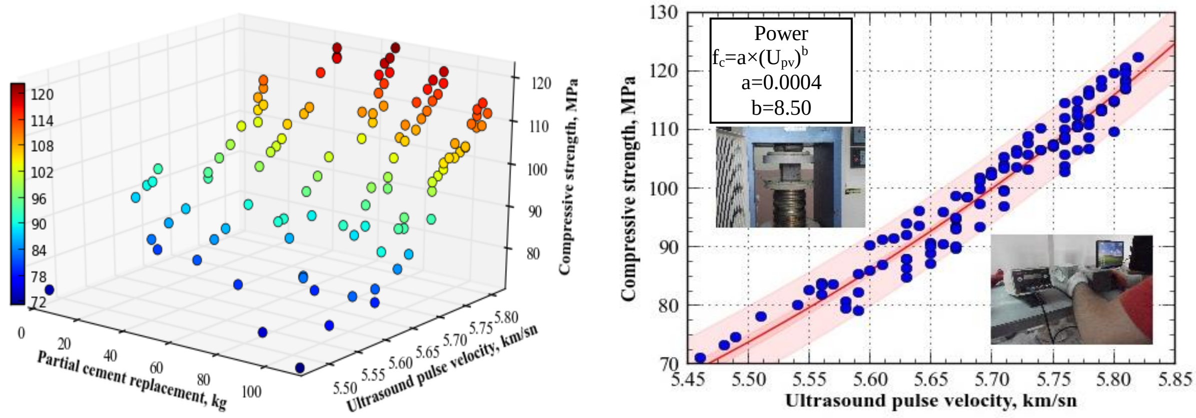
Fig. 4. SEM morphology of cementitious materials: a) The control concrete, b) The concrete containing A15, c) The concrete containing N5 and d) The concrete containing A15+N5

a) Relationships between compressive strength and ultrasound pulse velocity

The relationship between the partial cement replacement, U_{pv} and cube f_c values at the ages of 7, 28, 56, 91 and 365 days obtained from experimental studies are given in Fig. 5a as three-dimensional. As seen in this figure, if the U_{pv} value is high, the f_c value is high; and if the U_{pv} value is low, the f_c value is low. In addition, both U_{pv} and f_c have higher values if the partial cement replacement values are between 40 and 90 kg (approximately 10% and 20%) according to Fig. 5a. The relationship between the U_{pv} and cube f_c values at the ages of 7, 28, 56, 91 and 365 days obtained from experimental results of HSC containing SF, GP and SF in combination with GP are evaluated by using power regression model as seen in Fig. 5b. Also, the parameters and values of power regression model are given in Table 4. High correlation between the U_{pv} and cube f_c values is determined as shown in Fig. 5b. This high correlation is clearly confirmed by the standard error, R and R^2 values shown in Table 4. R^2 value obtained from the comparison is close to one. This value shows that a very good relationship between the U_{pv} and cube f_c values, and also f_c values can be calculated from U_{pv} values.

Table 4. Results of linear and power regression models

Regression type	Equation	Parameters				Std Error	R	R^2
			Value	Std Error	Range (95% confidence)			
Power	$f_c=a\times(U_{pv})^b$	a	4×10^{-5}	0.00001	0.00001 to 0.00007	3.013	0.971	0.936
		b	8.5	0.21005	8.07324 to 8.90595			
Power	$f_{sts}=a\times(f_c)^b$	a	0.77	0.08236	0.5991 to 0.9427	0.045	0.963	0.940
		b	0.37	0.02320	0.3227 to 0.4195			
Linear	$f_{fs}=a+b\times(f_c)$	a	4.25	0.38910	3.4354 to 5.0587	0.177	0.925	0.894
		b	0.042	0.00388	0.0342 to 0.0504			
Power	$f_{fs}=a\times(f_{sts})^b$	a	1.22	0.15632	0.8954 to 1.5475	0.132	0.959	0.926
		b	1.34	0.08824	1.1540 to 1.5221			



a) b)

Fig. 5. a) Effect of partial cement replacement on the U_{pv} and f_c, b) the relationship between the U_{pv} with f_c

The experimental f_c values are compared with f_c values obtained by using power regression model as seen in Fig. 6. The comparison shows that these values are close to each other. This situation is verified by R^2 values given on Fig. 6.

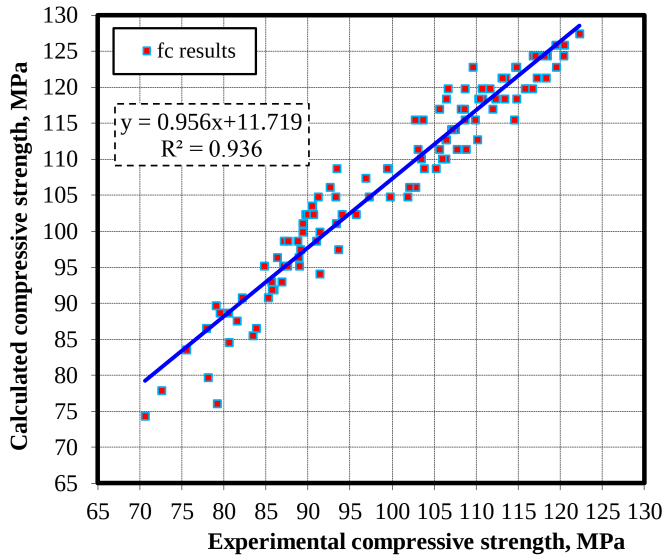
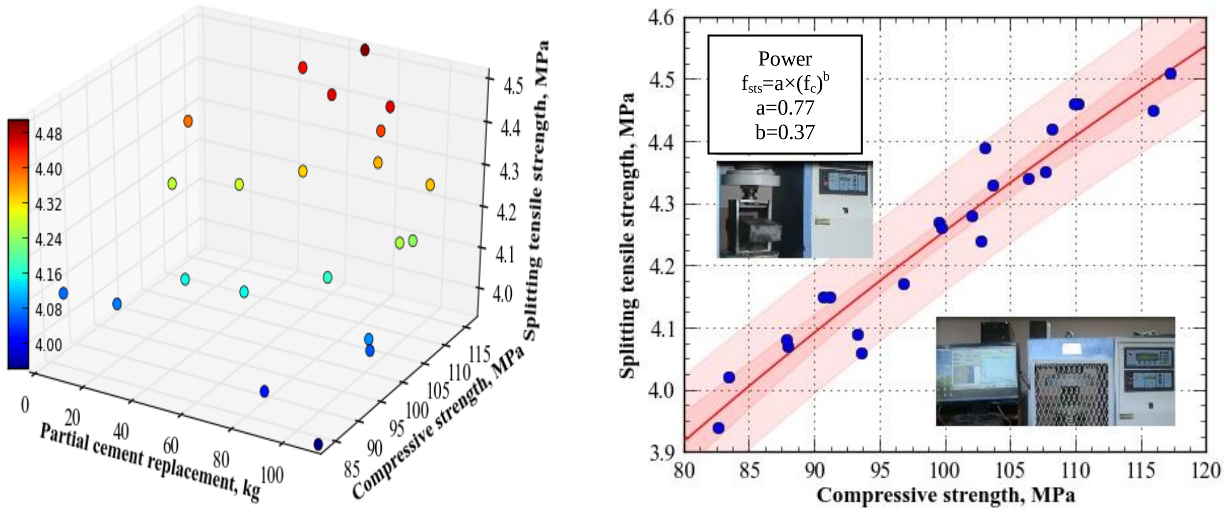


Fig. 6. Comparison of f_c values obtained from experimental studies and by using U_{pv}

b) Relationships of compressive strength with splitting tensile and flexural strengths

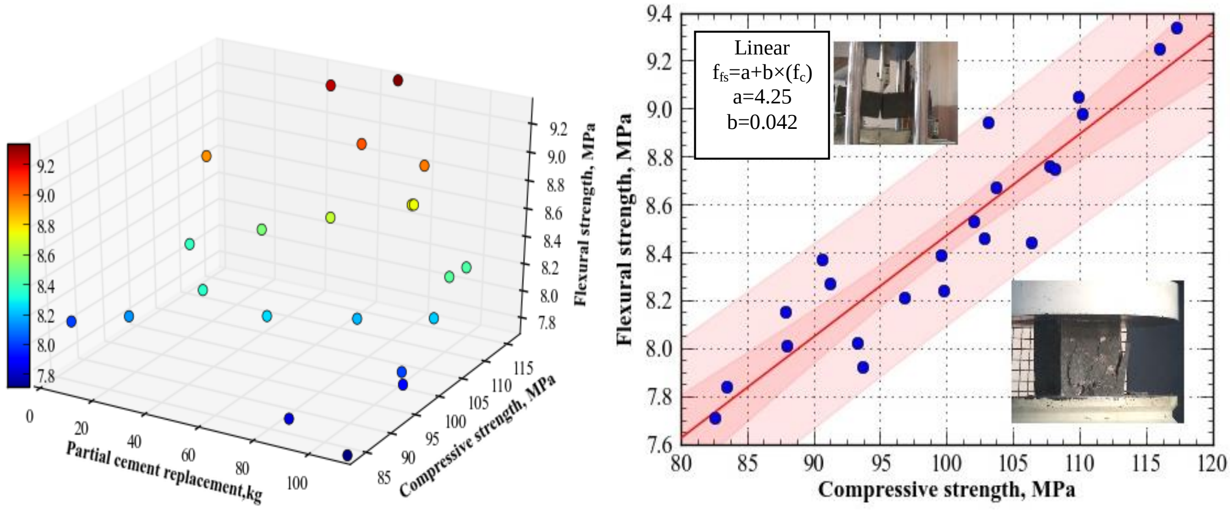
The relationships of partial cement replacement and cube f_c values at the age of 28 days obtained from experimental studies with the f_{sts} and f_{fs} values are given in Fig. 7a and 8a as three dimensional, respectively. As seen in these figures, if the partial cement replacement values are between 40 and 90 kg (approximately 10% and 20%) and the f_c value are high, the f_{sts} and f_{fs} values are high. But the increase in the f_{sts} and f_{fs} values is not more then the increase at the f_c values. The relationships between the f_{sts}-f_c and the f_{fs}-f_c values at the age of 28 days obtained from experimental results of HSC containing SF, GP and SF in combination with GP are obtained by using linear and power regression model as seen in Fig. 7b and 8b. The values obtained by using these regression models show that there is a significant relationship of the f_{sts}-f_c and the f_{fs}-f_c values. This situation is clearly shown by the statistical parameters given in Table 4.

The experimental f_{sts} and f_{fs} values are compared with the f_{sts} and f_{fs} values obtained by using linear and power regression models for the f_c values as seen in Fig. 9 and 10, respectively. The comparison shows that these values are close to each one. The equations given in Table 4 and obtained by linear and power regression models are used for calculating the f_{sts} and f_{fs} values from the f_c values.



a) b)

Fig. 7. a) Effect of partial cement replacement on the f_{sts} and f_c, b) the relationship between the f_{sts} with f_c



a) b)

Fig. 8. a) Effect of partial cement replacement on the f_{fs} and f_c, b) the relationship between the f_{fs} with f_c

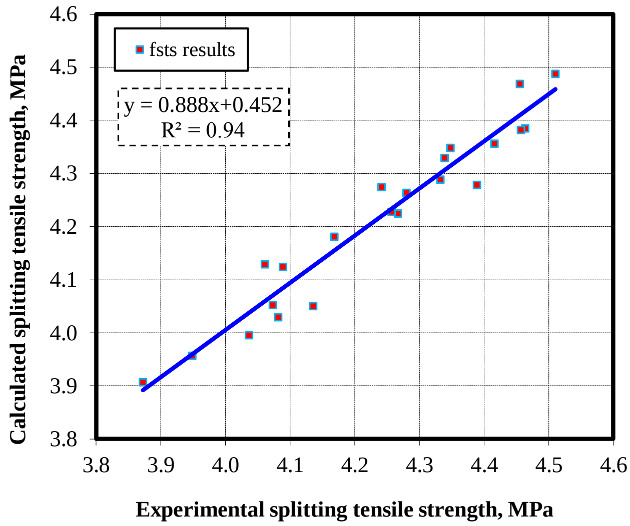


Fig. 9. Comparison of f_{sts} values obtained from experimental studies and by using f_c

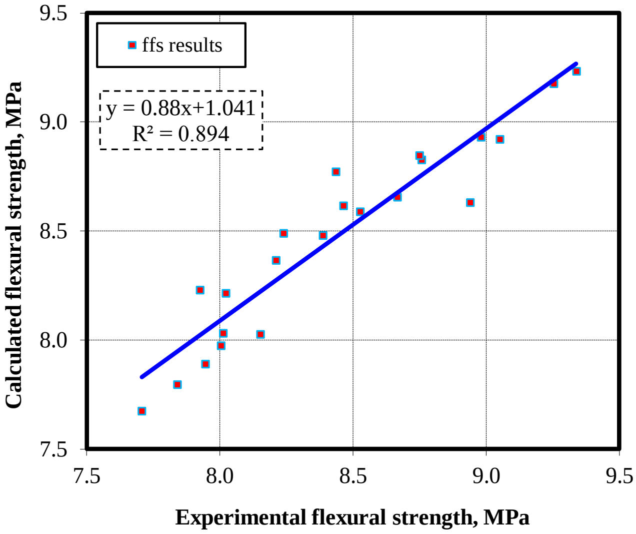
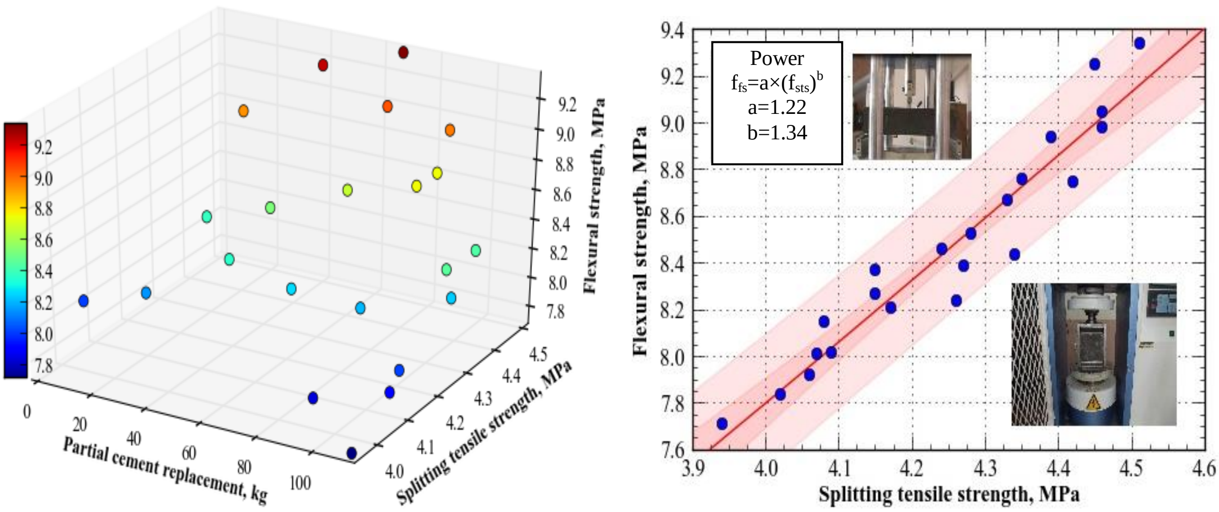


Fig. 10. Comparison of f_{fs} values obtained from experimental studies and by using f_c

c) Relationship between splitting tensile strength and flexural strength

The relationship between partial cement replacement, the f_{sts} and f_{fs} values at the age of 28 days obtained from experimental results of HSC containing SF, GP and SF in combination with GP is given in Fig. 11a as three-dimensional. As shown in this figure, the highest f_{sts} and f_{fs} values were obtained while the partial cement replacement value is approximately 65 kg (15% partial cement replacement ratio). The relationship between the f_{sts} and f_{fs} values at the age of 28 days was obtained by using power regression model as seen in Fig. 11b. The comparison of the experimental f_{fs} values with the f_{fs} values obtained by using power regression model for the f_{sts} values is seen in Fig. 12. A significant relation between the f_{sts} and f_{fs} values is expressed from this comparison and the statistical parameters given in Table 4. The equation obtained by using power regression model for the f_{sts} values is used for calculating the f_{fs} values of HSC.



a) b)

Fig. 11. a) Effect of partial cement replacement on the f_{fs} and f_{sts}, b) the relationship between the f_{fs} with f_{sts}

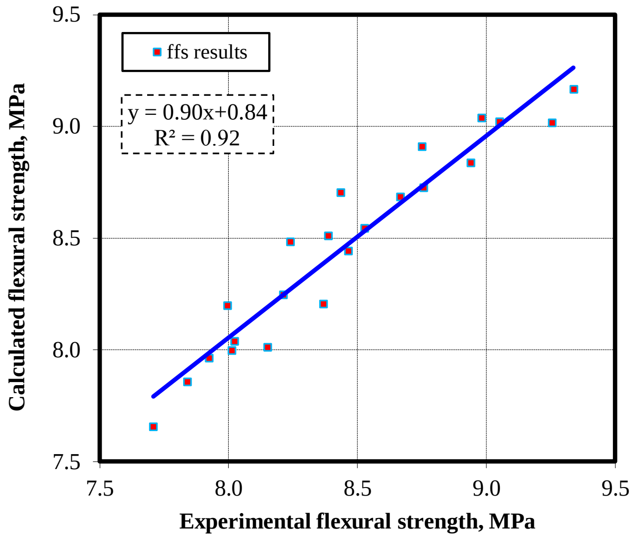


Fig. 12. Comparison of f_{fs} values obtained from experimental studies and by using f_{sts}

5. CONCLUSION

The aim of the present paper is to evaluate the effect of SF, GP and SF in combination with GP admixtures on the strength properties of HSC. Therefore, the U_{pv}, f_c, f_{sts}, and f_{fs} values of the control concrete and the concretes containing SF, GP and SF in combination with GP were determined by experimental study with the water-binder ratio of 0.25. Based on the results and discussion, the following conclusions can be drawn from this paper.

- The use of SF to replace cement by weight increases the U_{pv}, f_c, f_{sts}, and f_{fs} values according to control mixture. In particular, the use of A15 to replace cement by weight provides the highest U_{pv}, f_c, f_{sts}, and f_{fs} values.
- The use of N5 to replace cement by weight increases the U_{pv}, f_c, f_{sts}, and f_{fs} values according to control mixture at all ages while the other use of GP decreases the U_{pv}, f_c, f_{sts}, and f_{fs} values. The highest U_{pv}, f_c, f_{sts}, and f_{fs} values were obtained from the concrete mixture containing N5.
- The use of SF in combination with GP to replace cement by weight increases the U_{pv} and f_c values according to control mixture at all ages. The highest U_{pv} and f_c values are obtained from the concrete mixture containing A15+N5.
- The use of SF in combination with GP to replace cement by weight increases the f_{sts} and f_{fs} values according to control mixture. The highest f_{sts} and f_{fs} values were obtained from the concrete mixture containing A10+N5.
- The contribution of SF on the f_c values becomes more pronounced at early ages according to later ages, while the contribution of GP on the f_c values becomes more pronounced at later ages according to early ages.
- The results of equations obtained by regression analysis models are in good agreement with the experimental results for the U_{pv}, f_c, f_{sts}, and f_{fs} values. These equations can be used for determining the f_c from U_{pv}, f_{sts} and f_{fs} from f_c and f_{fs} from f_{sts} values for HSC.

The experimental results indicate that, HSC can be obtained with SF, GP and SF combination with GP. In particular, it is recommended that 15% by weight of SF can be utilized as a replacement for cement to obtain HSC with excellent properties.

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