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Fresh and Mechanical Properties of High-Performance Self-Compacting Concrete Containing Ground Granulated Blast Furnace Slag and Polypropylene Fibres

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Abstract: The purpose of this study was to evaluate the appropriateness of polypropylene fibres (PP) to decrease the brittleness of high-performance self-compacting concrete (HPSCC). The influence of PP fibre content on the fresh and mechanical assets of PP-fibre-reinforced HPSCC was investigated. PP fibres were applied with 0, 0.025, 0.05, 0.075, 0.125, 0.25% contents to the HPC blends with high cement replacement by ground granulated blast furnace slag (GGBS). The impact of PP fibre fraction on fresh properties of HPSCC, counting passing capability as well as filling parameters is discussed. In addition, the mechanical properties, i.e., compressive, splitting tensile, and flexural strengths, were evaluated after 7 and 28 days of specimens' maturation in water. The higher content of PP fibres gradually reduced the HPSCC workability and improved the mechanical properties. The high performance of fresh and hardened ecological HPSCCs containing 46% GGBS instead of cement with 0.025–0.25% PP fibre content proves the great potential of using these composites in various applications in the construction industry. The advantages of the potential recycling of GGBS include, among others, the reduced use of cement in a durable material, reduced amount of waste in landfill and lower emission levels of greenhouse gases.

Keywords: fresh and mechanical properties; ground granulated blast furnace slag; polypropylene fibre; self-compacting concrete

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1. Introduction

Self-compacting concrete (SCC) has different properties compared with the ordinary concrete regarding its fresh and mechanical behaviour. A number of studies have been carried out to determine the benefits of incorporating various cement replacement materials into SCC. These materials reduce the cost of SCC resulting from the significant amount of cement that is necessary to provide the required filling and passing ability. Decreasing or eliminating the use of cement in SCC seems imperative for both environmental and economic reasons. Ground granulated blast furnace slag (GGBS) is used in SCC as a replacement for cement due to its natural binding properties. The addition of GGBS reduces the permeability and increases the chemical stability of SCC due to the reaction of blast furnace slag with an excess of soluble calcium hydroxide [1]. As a consequence, it has an impact on the overall improvement of the durability of reinforced concrete structures [2].

The dense microstructure of high-performance concrete (HPC) warrants an increase in the compressive strength and permeability, but at the same time it has a negative impact on the brittleness and fire resistance [3]. Fibres are widely applied to strengthen HPC in order to improve the strength and energy absorption capacity, as well as to reduce explosive spalling in a fire [4]. To delay the development of micro-cracks and to enhance the toughness in HPC, nanomaterials such as multi-layer graphene, carbon tubes, and carbon nanofibres can be successfully added [5]. On the other hand, in order to monitor the crack growth process in HPC, embedded piezoelectric aggregates described in [6] can be used for the evaluation of the degree of damage of brittle materials in HPC. However, steel fibre is most commonly used to prepare HPC and ultra-high-performance concrete (UHPC) [7–9]. In this investigation, polypropylene (PP) fibre was used to produce environmentally friendly and cost-effective HPC. It should be noted that steel fibre is more expensive, is not environmentally friendly, corrodes easily, is affected by magnetic and electric fields, and can be harmful to workers [10]. The use of PP fibres does not raise any objections as to thermal conductivity, fire resistance and corrosion of fibres enclosed in a concrete matrix [11]. Due to the long-term durability of PP fibres in an aggressive environment due to excellent chemical stability and hydrophobicity, scientists turned their attention to their use in HPC [12,13]. It has been found that PP fibres are effective in reducing plastic shrinkage, delaying the formation of first cracks and controlling crack development [14–17]. However, PP fibres are most commonly used to control plastic shrinkage cracks due to its relatively low tensile strength [18–20]. In addition, several studies have reported that polypropylene fibres can hold a stable concrete mix without settling its constituents [21,22], which can be extremely important in self-compacting concrete mixes. On the other hand, the influence of PP fibres on the mechanical properties of HPC is not entirely clear, which is presented in the literature review below.

Zollo et al. [23] examined the compressive strength, splitting tensile strength and flexural strength of normal strength concrete without fibres and with the addition of PP fibres up to 0.3% volume content. Their results indicated that the presence of fibres had a negative effect on the compressive strength, while the flexural and splitting tensile strengths slightly increased with increasing fibre content. Similar results were also observed by other researchers [24,25]. Jiang et al. [26] reported a 3% decrease in the 90 day compressive strength of PP-fibre-reinforced, normal-strength concrete with compared to the reference one. Komlos et al. [27] noted that the PP fibre has no significant effect on the compressive strength of concrete. Mindess and Vondran [28] stated that the compressive strength of ordinary concrete increased by 25% with a 0.5% PP fibre volume fraction. Çelik and Bingöl [29] studied, inter alia, the effect of 0.15–0.30% volume content of PP fibres on the rheological and mechanical properties of SCC. Compressive strength decreased with increasing fibre content in all SCC mixtures. The highest compressive strengths for PP fibre reinforced concrete were achieved with a 0.15% fibre fraction. A noteworthy improvement in the flexural strength of all SCCs was obtained with the increase in fibre content, compared to plain concrete. Nili and Afroughsabet et al. [30] reported that 0.3% by volume of PP fibres increased the flexural strength of concrete by approximately 11.5%. Mazaheripour et al. [31] studied the strength of self-compacting lightweight concrete with the addition of PP fibre and found that the use of 0.1%, 0.2% and 0.3% PP fibres provided flexural strength increases of 5%, 8.5% and 10.5 % respectively compared to the reference concrete. Sadrinejad et al. [32] established that the hybrid effect of PP and polyolefin fibres improved compressive and tensile strength and reduced corrosion, but their excessive content can already cause the opposite effect. Wang et al. [33] studied the mechanical properties of HPC reinforced with polypropylene fibres. Test results indicated that, the strength of polypropylene fibres reinforced HPC increased with the increase of the fibre volume fraction. However, the compressive strength increased slightly, while the splitting tensile strength and flexural strength were improved significantly. The research also showed that the chemical adhesion between the PP fibre and the matrix is low, which may be influenced, among others, by the smooth surface of this fibre [34]. In addition, a water film forms at the interface between the fibre and the concrete matrix, which has a negative impact on the bond strength, because portlandite crystals increase their volume in the water environment and consequently increase the porosity in the contact zones [35]. In order to use the fibre strength and improve the overall properties of the composite, it is necessary to strengthen the interfacial bond strength of the PP fibres to the HPC matrix. Chan and Chu [36] found that silica fume added to the RPC matrix significantly improves the bonding of the steel fibre to the matrix due to the interfacial hardening effect during fibre sliding. Yazıcı et al. [37] established that GGBFS can be used as an alternative silica source in RPC. Mohamed and Najm [1] stated that cement replacement with the optimum value of 35% GGBS gave the highest 28 day compressive strength in the dosing range from 10 to 80%. On the other hand, Meyer [38] reported that the optimum cement replacement level is about 50% and sometimes as high as 70% and 80%. Therefore, it is possible that the physical and chemical interactions of the GGBS particles may be effective in improving this adhesion.

Many studies have shown that GGBS and PP fibres can be advantageously used in concrete applications. To the best of the author's knowledge, there are no research reports on the hybrid influence of PP fibres and steel industry by-products, i.e., GGBS, on the rheological and mechanical characteristics of high-performance self-compacting concrete (HPSCC). In this study, PP fibres were added to HPSCC to control the microcracks development, and GGBS was added to enhance the interfacial bond strength between fibres and the matrix and modify its microstructure. Firstly, the filling and passing ability of GGBS-modified, fresh, PP-fibre-reinforced HPSCC was studied by slump flow and L-box tests. Secondly, the impact of PP fibre content on compressive, tensile splitting, and flexural strength in HPSCC was investigated by using strength tests. Thirdly, the strength models are proposed to predict compressive, splitting tensile and flexural strength based on experimental results. The objective of this research was to evaluate fibre content, rheological characteristics, mechanical properties and strength models of HPSCC for construction applications.

2. Research Program

2.1. Materials, Mix Compositions and Specimens' Production

The experimental program was planned and performed analogously to the description presented in the previous conference publication [39]. The ingredients used to make SCCs incorporated cement (C), sand (S), gravel (G), ground granulated blast furnace slag (GGBS), water (W), as well as a mix of three kinds of high range water-reducing admixtures (HRWA). To study the influence of polypropylene fibre on the fresh properties and strength development of ecological SCCs, a control mix without fibre was developed in which ordinary Portland cement CEM I 42.5R, complying with PN-EN 197-1:2012 standard [40], and GGBS were used as binder components. Fibre-reinforced concrete mixtures were made with the addition of PP fibres to the reference mix in 0.025, 0.05, 0.075, 0.125, and 0.25% fractions. The specific chemical compositions of the cement and GGBS are given in Table 1.

Table 1. Chemical constituents of cement and GGBS (in %).

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	Cl	LOI	Insoluble Matter
Cement	20.19	4.30	3.25	64.61	1.41	2.96	2.59	0.26	0.111	3.41	0.48
GGBS	33.14	13.55	1.30	43.36	6.48	0.29	0.31	0.29	0.006	0.76	0.31

The high content of SiO_2 in GGBS was advantageous in terms of material strength.

In all compositions, three types of HRWAs based on lignosulfonates and polycarboxylic ethers were applied. Their total amount was kept at 3% of the weight of binders in all mixes. The HRWA dose was selected to obtain the slump flow of 720 ± 10 mm for the reference blend, meeting the requirements for the SF2 flow class in accordance with the European guidelines [41]. The total amount of cementitious materials was 650 kg/m^3 and the W/B ratio was maintained at 0.32. As a coarse aggregate, gravel with a maximum diameter of 8 mm was used in the amount of 400 kg/m^3. Quartz sand with a fineness modulus of 1.84 and a grain size of 0.5/2 mm was used in the amount of 980 kg/m^3. The particle sizes of gravel and quartz sand were determined in accordance with a known standard. The polypropylene fibre was provided by BAUCON® Co. (BAUTECH®, Piaseczno, Poland). It was crimped with 12 mm length and 25 µm diameter filaments. Other PP fibre properties, based on the manufacturer's technical data, were as follows: density 910 kg/m^3, modulus of elasticity 35,000 N/mm^2 and tensile strength = 350 N/mm^2. Polypropylene fibres used in this study are shown in Figure 1.

Figure 1. Polypropylene fibres used in the tests.

The mixed compositions of polypropylene-fibre-reinforced HPSCCs are displayed in Table 2. HPSCC denotes the plain concrete and PPHPSCC indicates the PP-fibre-reinforced concrete. The number directly following the abbreviation represents the percentage of PP fibres. The amount of the other ingredients was identical in order to determine the impact of the PP fibre on the self-compacting concrete properties.

Table 2. HPSCC and PPHPSCC mixture proportions (kg/m^3).

Designation	Cement	GGBS	Quartz Sand	Gravel	Water	HRWA	PP Fibre
HPSCC	350	300	980	400	210	19	—
PPHPSCC-0.025	350	300	980	400	210	19	0.23
PPHPSCC-0.05	350	300	980	400	210	19	0.46
PPHPSCC-0.075	350	300	980	400	210	19	0.68
PPHPSCC-0.125	350	300	980	400	210	19	1.14
PPHPSCC-0.25	350	300	980	400	210	19	2.28

The mixing procedure for PPHPSCC is presented in Figure 2. The order of adding the mix components was as follows: gravel and quartz sand (G+S), cementitious materials (C+GGBS), uniformly mixed water (W) with three types of HRWAs, as well as polypropylene fibres (PP). The times of mixing for above components were 2, 2, 4, and 4 min, respectively. Then, the L-box and slump flow tests were performed. After the tests of rheological properties, the moulds were filled with concrete and left covered with foil for 24 h in the laboratory. The specimens were then demoulded and placed in a tank with water at 20 ± 2 °C to mature for testing.

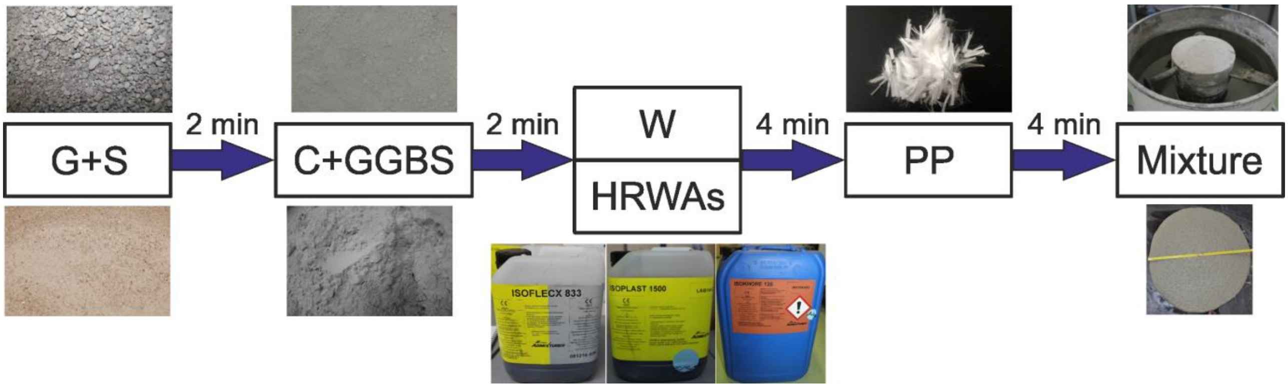

Figure 2. Diagram of PPHPSCC mixing process.

2.2. Research Methodology

This research was planned to evaluate the influence of polypropylene fibre content on the fresh mix factors and mechanical assets of PPHPSCC. In order to obtain parameters of workability, the L-box and slump flow examinations were performed in accordance with the European Guidelines for SCC [41]. The L-box experiment was made using an L-shaped vertical box. Initially, the vertical part of the L-box was filled with the mix. After 1 min, the gate was raised to allow its passing through three steel rebars and fill the horizontal part of the equipment (see Figure 3). The distance measurements were made at both ends of the box in six evenly spaced places between its upper edge and the concrete level. In the next step, the average distance of the mix from the top of the box was calculated and then the depth ratio was determined. This ratio corresponds to the mix's passing ability (PA). During the slump flow test, we measured the maximum flow diameters in two directions and the time (T_{500}) in which the PPHPSCC mix reached a diameter of 500 mm.

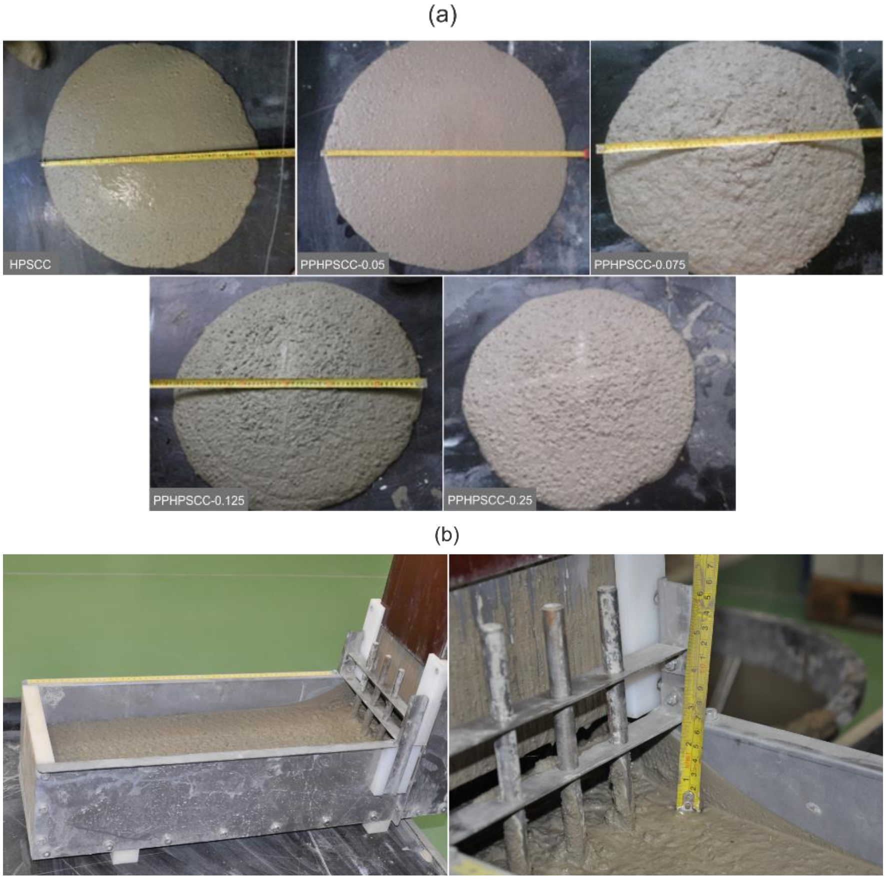

Figure 3. Slump flow diameter measurement (**a**) and height of L-box filling (**b**).

The mechanical properties of PPHPSCCs were established at 7 and 28 days of maturation in water. The strength under compression test was performed using a testing machine of 3 MN capacity in accordance with PN-EN 12390-3 [42] on cubes of 100 × 100 × 100 mm. Each cube was tested up to failure. The load rate was 0.5 MPa/s. Cubic samples (12 for each mix) were tested at two ages of maturation. Then, the average value of this strength was taken as the compressive strength of this mix. The PPHPSCCs split tensile strength was examined using the testing machine according to PN-EN 12390-6 [43]. Specimens were loaded at a rate of 0.05 MPa/s. Cubes of 100 × 100 × 100 mm size (12 for each mix) were tested for each mix at 7 and 28 days of curing. The mean value of this strength was taken as the splitting tensile strength. The bending test of PPHPSCCs was performed at three-point loading scheme with using a hydraulic machine in accordance with PN-EN 12390-5 [44]. Prismatic specimens were loaded at a rate of 0.05 mm/min. 100 mm × 100 mm × 500 mm size prismatic specimens (6 for each mix) were examined at two curing ages, as well as the mean value of the flexural strength was determined for each testing mix.

3. Results and Discussion

3.1. Rheological Parameters

PPHPSCCs mixes were evaluated for fresh parameters such as filling ability throughout slump flow test as well as passing ability during L-box test. The parameters of fresh mixes are listed in Table 3.

Table 3. Fresh properties of HPSCC and PPHPSCC.

Designation	HPSCC	PPHPSCC-0.025	PPHPSCC-0.05	PPHPSCC-0.075	PPHPSCC-0.125	PPHPSCC-0.25
Slump flow (mm)	722.5	715	705.5	580.5	570	485
T_{500} (s)	4.1	4.3	4.5	4.8	5	—
L-box, PA	0.94	0.90	0.88	0.85	0.82	0.63

Figure 3 illustrates the typical slump flow diameter measurement and height of L-box filling. The slump flow diameters of the reference HPSCC and PPHPSCCs mixes are shown in Figure 4. The HPSCC control mix reached the maximum flow diameter of 722.5 mm. The diameter of PPHPSCC mixes flow were within the range of 570–715 mm. Except for the PPHPSCC-0.25 mix with the highest content of PP fibres, the slump flow diameter of other mixes complied with the requirement of European guidelines for SCC [41]. The HPSCC, PPHPSCC-0.025, and PPHPSCC-0.05 mixes were categorised as SF2 class, as the slump flow results were in the range of 660–750 mm. The mixes of class SF2 are appropriate for columns and walls. On the contrary, the PPHPSCC-0.075, and PPHPSCC-0.125 mixes were categorised as SF1 class due to the obtained flow diameters between 550 and 650 mm. The mixes of SF1 class are appropriate for tunnel linings, housing slabs, deep foundations and piles.

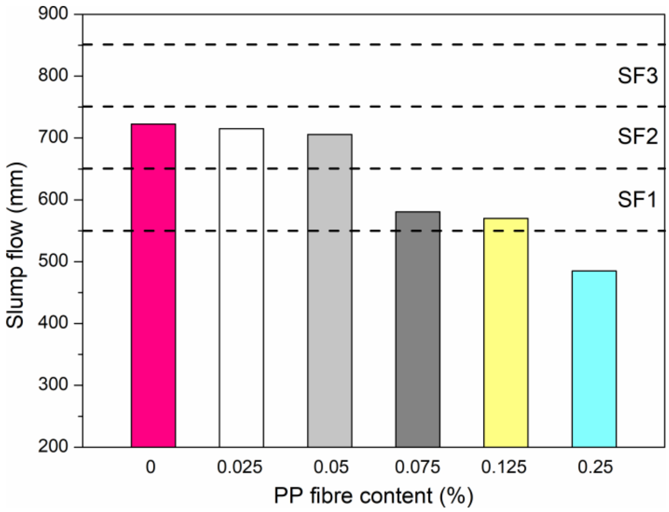

Figure 4. Variation of slump flow diameter with different PP fibre volume content.

All the mixes of PP-fibre-reinforced concrete reached the maximum flow diameter that was lower than the control mix, which indicates a negative influence of the PP fibre inclusion on the workability (Figure 3a). The impact of increased PP fibre fraction on worsened flowability of the HPSCC corresponds to previous conclusions [29,45–47]. The T_{500} time given in Table 3 shows mixes with high viscosity. Each of the mixes was characterized by a flow time of 4.1 to 5 s. Figure 5 shows the L-box blocking ratio results of the reference HPSCC and PPHPSCCs mixes. These ratios (H_2/H_1) were obtained as values between 0.63 and 0.94 for all groups of mixes. The results indicate that the PP fibres decreased blocking ratios i.e., passing abilities, but there were in the range of 0.8–1, and in accordance with the guidelines [41], except the PPHPSCC-0.25 mix.

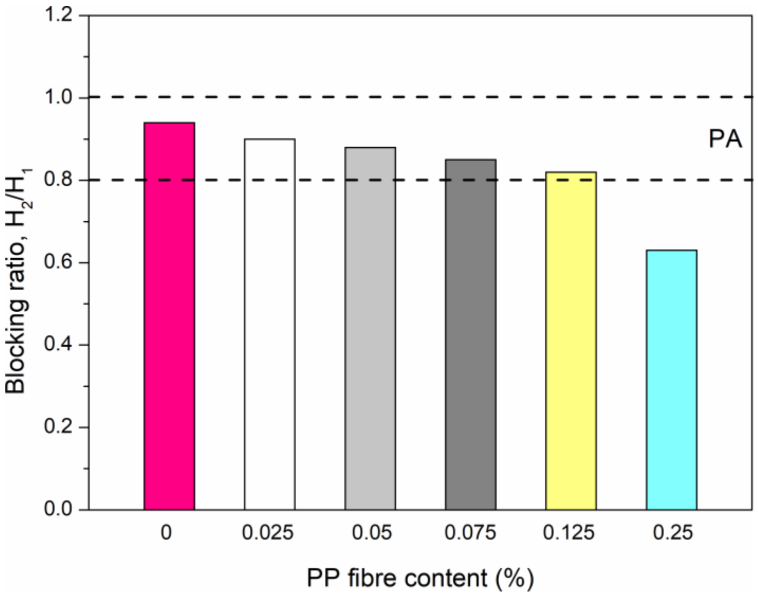

Figure 5. Variation of blocking ratio with different PP fibre volume content.

The tendency of the results obtained on the basis of testing the rheological properties of the mixes is consistent with the research of Ponikiewski [48]. Based on the rheometric analysis of the workability of the mixes with the addition of polypropylene fibres with a length of 3, 6 and 12 mm and the volume content of 0.1%, 0.2%, 0.3%, an increase in the viscous flow resistance was observed along with the increase in fibre content and its decrease after increasing the dose of superplasticizer.

3.2. Compressive Strength

The 7 day and 28 day compressive strengths of the HPSCC mixes containing PP fibre were determined. The cited values are the mean of six companion cube specimens, and there were tested per data point. The effect of PP fibre content on the development of the compressive strength is illustrated in Figure 6.

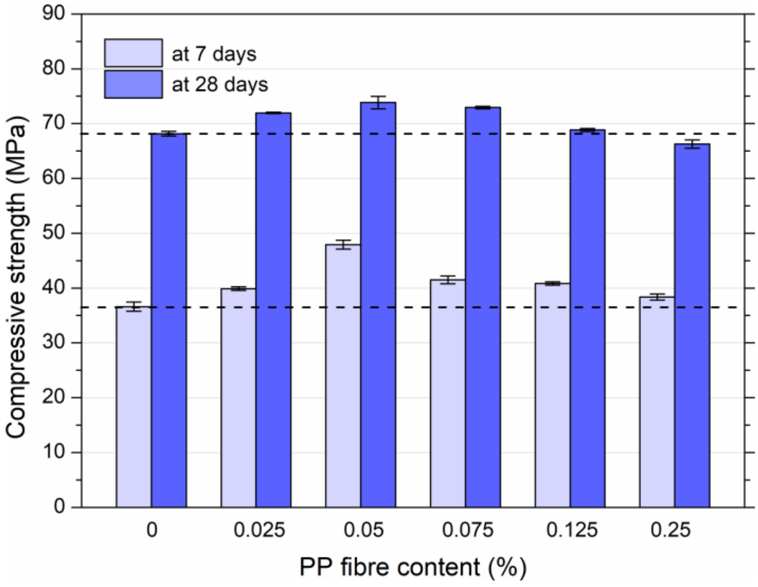

Figure 6. Compressive strength of PPHPSCC for different polypropylene fibre volume content.

As could be seen, the reference mix experienced less compressive strengths than the other mixes containing PP fibres at all ages. The exception was the 28 day strength of the PPHPSCC-0.25 blend containing the largest volume fraction of PP fibres, i.e., 0.25%. This strength was about 3% lower compared to the strength of the reference mix. The mix PPHPSCC-0.05 with 0.05% PP fibres possessed the highest values of strength. The results of the mix with 0.075% PP fibres (PPHPSCC-0.075) are the second-highest values. At 28 day, the addition of 0.125% PP fibres caused a marginal increase in PPHPSCC-0.125 strength over that of the reference cube specimens. The compressive strength of the PP-fibre-reinforced mixes was higher than that of the reference mix by about 9%, 31%, 13.5%, 11.5%, and 5% for 0.025%, 0.05%, 0.075%, 0.125%, and 0.25% PP volume fractions, respectively, at 7 day. On the other hand, at 28 day, the above-mentioned strengths were respectively higher by approximately 5.5%, 8.5%, 7%, and 1% for the first four volume fractions of PP fibres. In general, the increase in the compressive strength of fibre-reinforced concrete is attributed to the retardation of matrix fracturing by limiting and retarding crack propagation through the fibres. In this study, the author found that high volume fractions of polypropylene fibres adversely affected the workability of fresh HPSCC and therefore, holes were created in the PPHPSCC mixes. In fact, it is the formation of these voids that results in a decrease in compressive strength of high-performance self-compacting concrete. The tendency of changes in compressive strength with the increase in the volume content of polypropylene fibres is not unambiguous. For example, Murali et al. [49] reported that the compressive strength increases from 64 MPa for concrete without fibres to 107 MPa for the mixture with the 1.5% content of fibres when using polypropylene fibres with a length of 50 mm and fractions of 0%, 0.5%, 1% and 1.5%. Similar results were obtained by Grabiec et al. [50] based on tests of polypropylene fibres with a length of 48 mm. It was found that the fibre content at the levels of 0%, 2% and 4% has a positive effect on the compressive strength. Different results were obtained by Richardson et al. [51] studying the effect of 0.6 and 0.9 kg/m^3 of 19 mm, 38 mm and 50 mm fibre content on the concrete strength. They found that the lower density of polypropylene fibres compared to the matrix and breaks in the C–S–H bond caused by PP fibre inclusions resulted in lower compressive strength values. A decrease in compressive strength was also noted by Pająk and Ponikiewski [52] using fibres with lengths of 19 mm and 38 mm and their volume in a mixture of 0.3–0.9%. The increasing percentage decreased the strength of the material compared to the reference mixture; the strength decreased by 6% for 19 mm fibres and 8% for 38 mm fibres. In turn, Broda [53] reported that in the case of using fibres of length 5 mm, 10 mm and 15 mm with a percentage of volume in the mixture of 0.25%, 0.75% and 1%, a slight impact on the compressive strength was obtained.

The polynomial correlations between the compressive strength and volume fraction of polypropylene fibre after 7 and 28 days of moist curing are shown in Figure 7. Compressive strengths showed increased trends firstly, and then decreased trends with the PP fibre content from 0% to 0.25% due to PP fibres having a different impact on the strength of HPSCC. The 7 day and 28 day compressive strength of high-performance self-compacting concrete incorporating polypropylene fibres could be estimated by the below quadratic equations:

$$f'_{c7} = -330.19V_{PP}^2 + 78.96V_{PP} + 38.73 \tag{1}$$

$$f'_{c28} = -224.8V_{PP}^2 + 38.6V_{PP} + 70.22 \tag{2}$$

where f'_{c7} and f'_{c28} are the 7 day and 28 day compressive strength of cubic specimens (MPa), and V_{PP} is the polypropylene fibre volume content (%).

The correlation coefficient R^2 reached values of 0.283 and 0.533 for 7 day and 28 day compressive strength, respectively. The variabilities of these proposed relationships are large. Therefore, the reliability is bad. The scatter of data points may be due to the decrease in workability of HPSCC with the increase of PP fibre fraction and the agglomeration of these fibres.

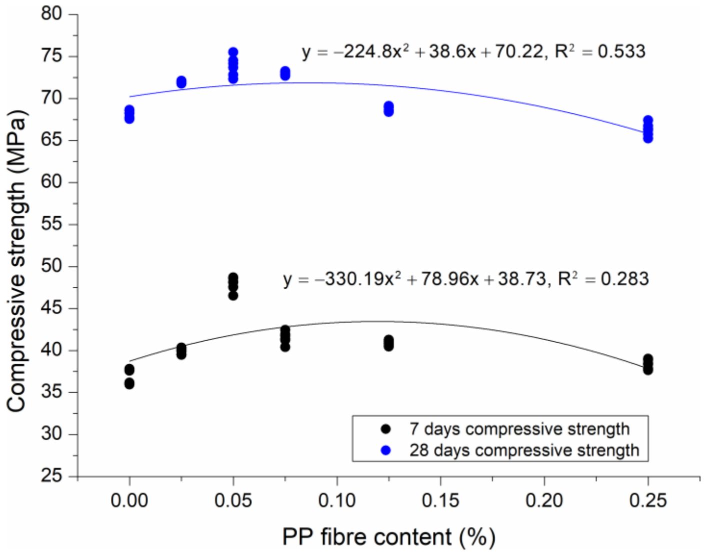

Figure 7. Correlations between 7 day or 28 day compressive strength and volume content of PP fibre.

Following the test results of the compressive strength, the 28 day compressive strength of HPSCC was predicted using the 7 day compressive strength and is expressed as a linear relation:

$$f'_{c28} = 0.57 f'_{c7} + 46.88 \tag{3}$$

The 28 day compressive strength prediction using Equation (3) agreed quite weakly with the test results illustrated in Figure 8. The linear trend was characterised by a weak correlation coefficient R^2 = 0.53 and relatively high errors in the intercept. The greatest dispersion of results was observed in the HPSCC groups with 0.05% PP fibres and the highest content of PP fibres equal to 0.25%. The derived equation should not be applied to predict the relationship between the 7 day and 28 day compressive strength of the HPSCC cube specimens studied herein.

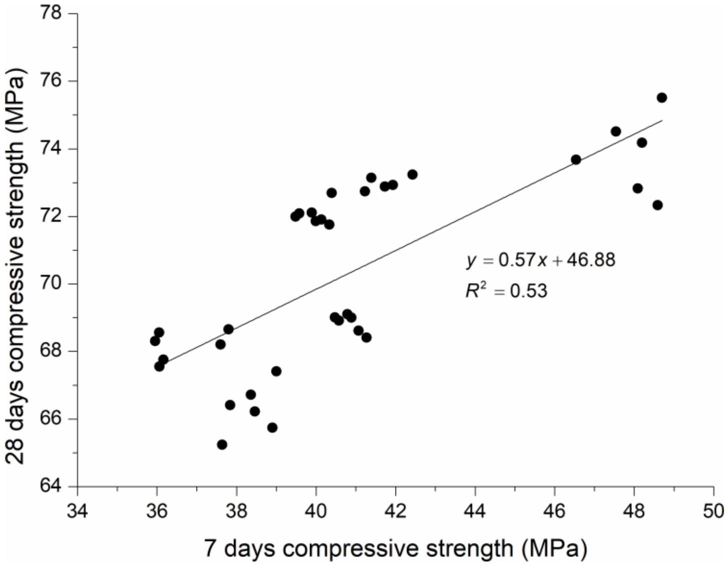

Figure 8. Correlation between 28 day and 7 day compressive strength for HPSCC and PPHPSCCs.

3.3. Splitting Tensile Strength

To further study the contribution of PP fibres to the tensile strength of PPHPSCC materials, splitting tensile tests were carried out on cube specimens with varying volume fractions of PP fibres, i.e., 0.025%, 0.05%, 0.075%, 0.125%, and 0.25%. Six cube specimens were prepared and tested for each mix and curing age. The mean strengths of different mixes when cured for 7 days and 28 days were compared, as shown in Figure 9.

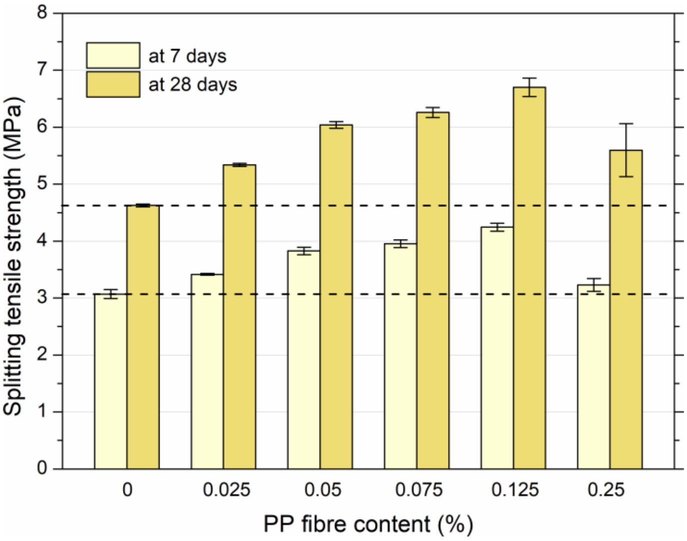

Figure 9. Splitting tensile strength of PPHPSCC for variable content of polypropylene fibres.

There were improvements in the splitting tensile strength effectiveness with increasing PP fibre content, with values of 11.5% and 15.5% at 0.025% PP fibre content, 25% and 30.5% at 0.05% content, 29% and 35% at 0.075% content, 38% and 44.5% at 0.125% content, and 5% and 21% at 0.25% content after 7 days and 28 days of curing, respectively. It can be noted that the 7 day splitting tensile strength improvements of PPHPSCC ranged from 11.5% to 38% at the volume contents of 0.025% to 0.25% in comparison with the reference HPSCC without PP fibres. On the other hand, the 28 day splitting tensile strength of PPHPSCC reached the improvements of 15.5% to 44.5% at the same PP fibre fractions. As expected, even a low content of polypropylene fibres increased the splitting tensile strength. Theoretically, the greater the number of fibres bridging the splitting crack, the greater the tensile strength should be. However, in this study, it was possible for self-compacting concrete to achieve the desired rheological parameters with a relatively low content of polypropylene fibres, i.e., 0.125%. Wang et al. [33] reported that the splitting tensile strength of HPC with 0.1–0.2% polypropylene fibres increased by 32.86–44.52% compared to HPC without fibre. Gołaszewski and Ponikiewski [54] noted an increase in splitting tensile strength from 3.75 MPa to 5.11 MPa with an increase in the content of polypropylene fibres 50 mm long and volume fractions from 0% to 1.5%.

Figure 10 shows the strong relationships between 7 day or 28 day splitting tensile strength and volume content of PP fibres regarding high-performance self-compacting concrete. Splitting tensile strengths displayed an increased trend initially, and then decreased tendencies with the PP fibre content decreasing from 0.125% to 0.25%, due to fibres having a different influence on the tensile strength of HPSCC. Direct relationships are completely clear according to high correlation coefficients equal to 0.96 and 0.91, respectively, with their equations in the form of a polynomial–quadratic function as seen below:

$$f_{ct,spl7} = -68.95V_{PP}^2 + 17.97V_{PP} + 3.05 \quad (4)$$

$$f_{ct,spl28} = -103.5V_{PP}^2 + 29.51V_{PP} + 4.68 \quad (5)$$

where $f_{ct,spl7}$ and $f_{ct,spl28}$ are the 7 day and 28 day splitting tensile strength of cubic specimens (MPa).

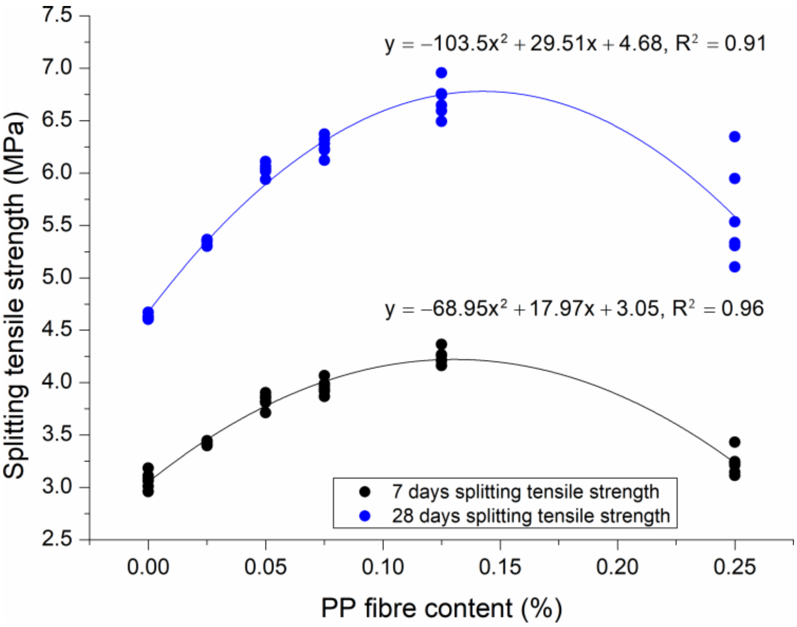

Figure 10. Correlations between 7 day or 28 day splitting tensile strength and volume content of PP fibre.

The greatest dispersion of the 7 day and 28 day splitting tensile strength results was noted with the highest content of PP fibres. This may be due to its agglomeration caused by a decrease in workability. Figure 11 exhibits the linear correlation between the 28 day and 7 day splitting tensile strength values of polypropylene-fibre-reinforced HPSCC. This correlation demonstrated a strong value of $R^2 = 0.94$. The predicted equation for HPSCC after 28 days of water curing is specified by:

$$f_{ct,spl28} = 1.64 f_{ct,spl7} - 0.23 \tag{6}$$

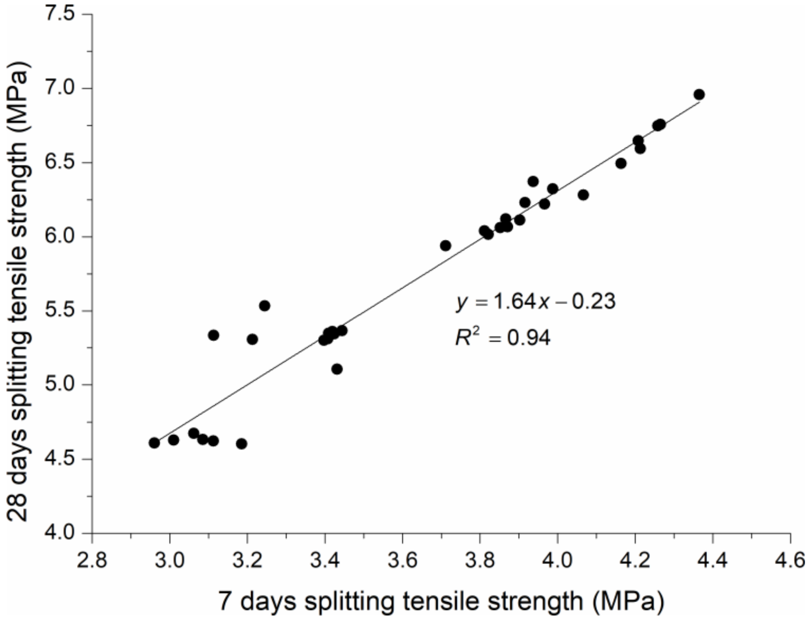

Figure 11. Correlation between 28 day and 7 day splitting tensile strength for HPSCC and PPHPSCCs.

The derived equation may successfully be used to predict the relationship between the 7 day and 28 day splitting tensile strength for HPSCC.

3.4. Flexural Strength

Flexural strength tests were performed at 7 and 28 days. Figure 12 displays the differences in the flexural strength of HPSCC with the various PP fibre contents.

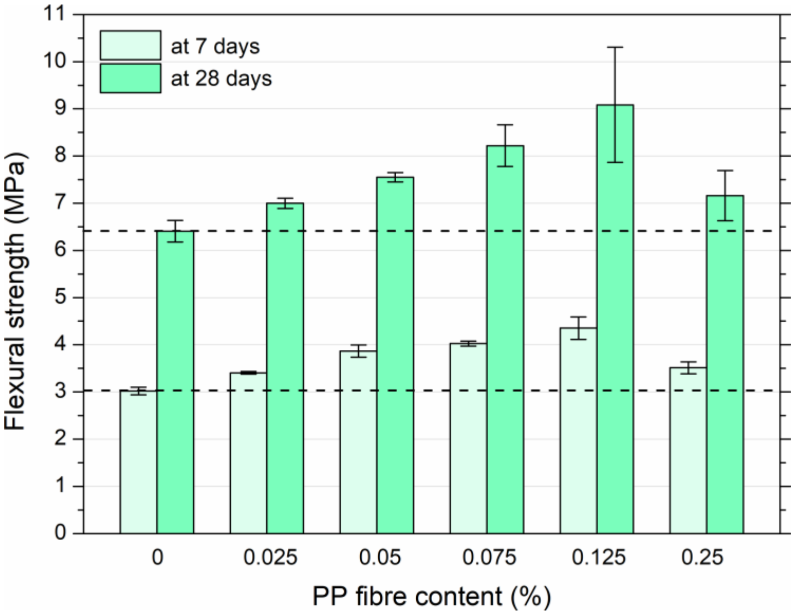

Figure 12. Flexural strength of PPHPSCC for different polypropylene fibre volume content.

The flexural strength effectiveness at 7 and 28 days indicates that the flexural strength values were higher by 12.5% and 9.5%, 29% and 18%, 33.5% and 28.5%, 45% and 42%, 16.5% and 12% at the volume contents of 0.025%, 0.05%, 0.075%, 0.125%, and 0.25% after 7 and 28 days, respectively, in comparison with HPSCC reference mix. During bending, the ends of the polypropylene fibres are pulled out of the cement matrix. Initially, the deformation of the interfacial transition zone occurs and the adhesion of fibres with different Young's moduli and deformability effects to the cement paste is disturbed. A further increase in load causes one end of the fibre to pull out while the other end is firmly anchored in the matrix. Wang et al. [33] reported that the flexural strength increased by 19.64% to 24.46% when the volume fraction of polypropylene fibre is in the range of 0.025% to 0.042%. Jasiczak and Mikołajczyk [55] noted an increase in flexural strength with increasing the fibre volume fraction for PP fibres with lengths of 48 mm and 60 mm at volume contents of 0.33–1%. Similar results were obtained using fibres with a length of 19 mm and 38 mm for a volume content of 0.3–0.9%. The increase in flexural strength was 25–59% and was greater for 38 mm-long fibres [52]. Based on the above-mentioned literature [33,52,55], it can be concluded that the use of polypropylene fibres with a length of 12–60 mm and a content of 0.3–1% is beneficial and increases the flexural strength.

The optimally fitted curves on the basis of the flexural strength and fibre content are presented in Figure 13, and it is pronounced that there are strong relationships between 7 day and 28 day flexural strength and volume fraction of PP fibres concerning HPSCC. Based on the results, the following quadratic functions between 7 day and 28 day flexural strength as well as PP fibre content with favourable correlation coefficients $R^2 = 0.93$ and $R^2 = 0.84$, respectively are obtained:

$$f_{ct,fl7} = -69.19V_{PP}^2 + 19.32V_{PP} + 3.01 \quad (7)$$

$$f_{ct,fl28} = -110.2V_{PP}^2 + 30.69V_{PP} + 6.37 \quad (8)$$

where $f_{ct,fl7}$ and $f_{ct,fl28}$ are the 7 day and 28 day flexural strength of prismatic specimens (MPa).

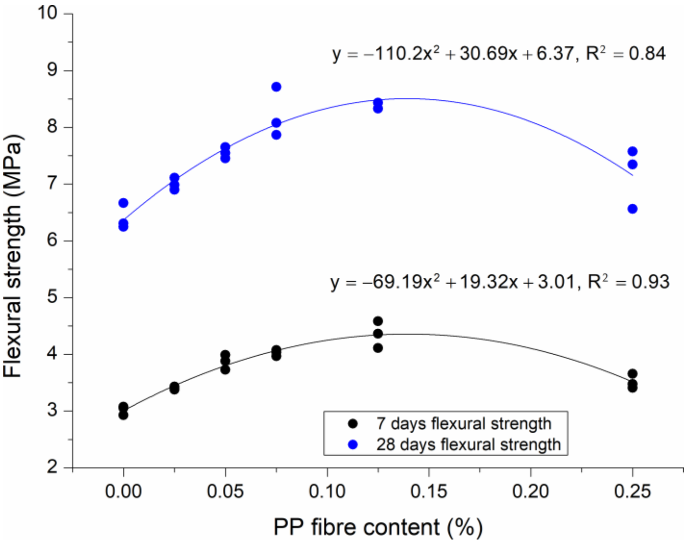

Figure 13. Correlations between 7 day or 28 day flexural strength and volume content of PP fibres.

The obtained curves are analogous to those for HPSCC splitting tensile strength. Ostle [56] found that the model can be considered as a reasonable when the R^2 coefficient is at least 0.7. For that reason, the obtained equations can be successfully used to predict the relations between the 7 day and 28 day compressive strength and the fibre content. According to the test data, the relation between the 28 day and 7 day flexural strengths PPHPSCC can be expressed as below, with Figure 14 presenting a comparison between the fitting linear function and test results. This relation established a quite strong value of R^2 = 0.86 for HPSCC with PP fibre content.

$$f_{ct,fl28} = 1.34 f_{ct,fl7} + 2.51 \tag{9}$$

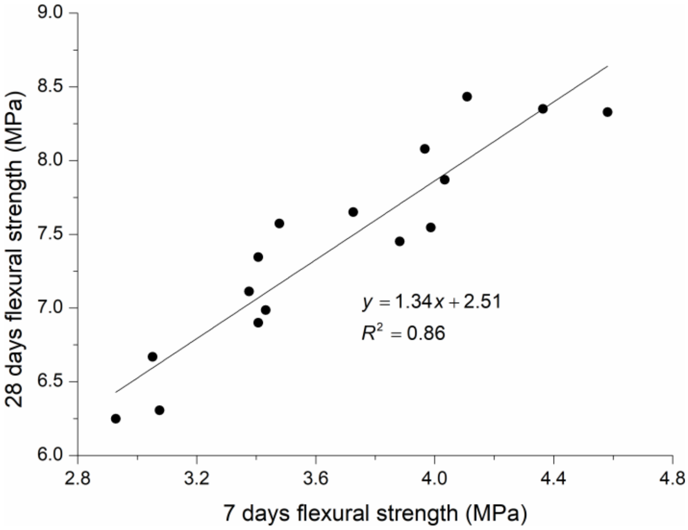

Figure 14. Correlation between 28 day and 7 day flexural strength for HPSCC and PPHPSCCs.

The linear relation between splitting tensile strength and flexural strength was obtained based on the regression analysis of the tensile strength results. Figure 15 and the following formula indicate the correlation between flexural strength and splitting tensile strength for HPSCC with PP fibres, which has a linear relationship with a strong coefficient of determination R^2 = 0.93.

$$f_{ct,fl} = 1.56 f_{ct,spl} - 1.76 \tag{10}$$

where $f_{ct,spl}$ is the splitting tensile strength of cubic specimens (MPa), and $f_{ct,fl}$ is the flexural strength of prismatic specimens (MPa).

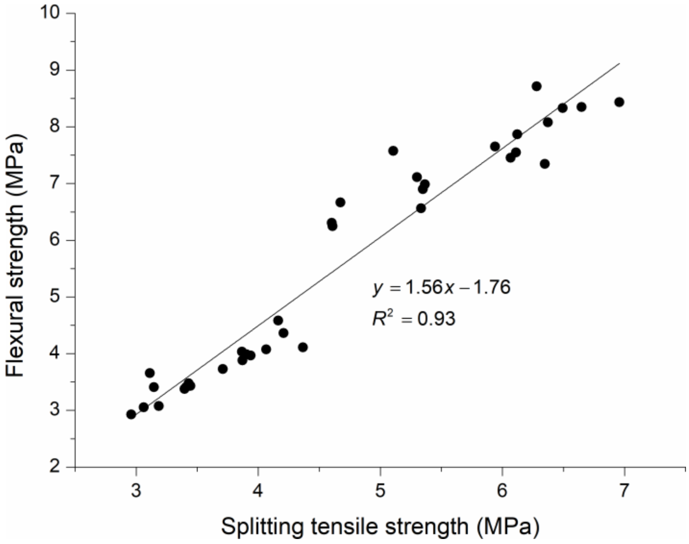

Figure 15. Correlation between flexural strength and splitting tensile strength for HPSCC and PPHPSCCs.

Based on the results, with the growth of splitting tensile strength, the value of flexural strength increases. The linear equation may effectively be applied to predict the linear relation between the splitting tensile and flexural strengths for HPSCC.

4. Conclusions

In these studies, sustainable, high-performance self-compacting concrete mixes providing good rheological and mechanical properties were developed. In all concretes GGBS was used as a cement replacement in the amount of 46% by cement weight and a constant water to binder ratio of 0.32. The following conclusions can be drawn from the conducted study:

- Workability of high-performance self-compacting concrete decreases as the content of polypropylene fibres increases. The T_{500} slump flow time is approximately 4 s for the reference HPSCC. In the other hand, the longest flow time was obtained for 0.125% PP-fibre-reinforced PPHPSCC. The blocking factor ranges from 0.63 to 0.94 and the increasing fibre fraction decreases passing ability.
- Polypropylene fibres have no statistically significant effect on the 28 day compressive strength of high-performance self-compacting concrete at the volume fractions used in this investigation. On the other hand, the addition of 0.05%, 0.075%, and 0.125% volume fraction of PP fibres increases the 7 day compressive strength by 31%, 13.5% and 11.5%, respectively. Minor effects are noted for the minimum and maximum volume fraction of PP fibres (for 0.025% and 0.25%) used in this study.
- Polypropylene fibres have noteworthy effects on the splitting tensile strength. The 7 day and 28 day strength improvements of PPHPSCC range from 11.5% to 38%, and from 15.5% to 44.5%, respectively, at the PP fibre volume contents of 0.025% to 0.25% in comparison with reference HPSCC. Greater increases in the splitting tensile strength are noted after 28 days of water curing.
- Polypropylene fibres affect the flexural strength significantly. The addition of 0.025%, 0.05%, 0.075%, 0.125%, and 0.25% volume fractions of PP fibres increases the flexural strengths at 7 and 28 days by 12.5% and 9.5%, 29% and 18%, 33.5% and 28.5%, 45% and 42%, 16.5% and 12%, respectively, in comparison with control HPSCC. In this case, greater increases in strength occur for the 7 day flexural strength.
- The strength models developed for HPSCC accurately predict 7 day and 28 day compressive strengths, tensile splitting strengths, and flexural strengths.

- In future works, studies of fracture parameters and durability properties of high performance self-compacting concrete containing ground granulated blast furnace slag and polypropylene fibers, as well as an evaluation of their microstructure, morphology, and pore structure, are planned.

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