Influence of superabsorbent polymer on the splitting tensile strength and fracture energy of high-performance concrete

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Abstract: Superabsorbent polymers (SAP) addition as an internal curing (IC) agent in concrete is an approach being adopted for the mitigation of autogenous shrinkage. Micro-voids created by SAP are arguably believed to be detrimental to the mechanical properties especially the fracture tendencies of the concrete. This paper presents the report of an experimental study of SAP's influence on the splitting tensile strength and fracture energy of low water/binder (W/B) high-performance concrete (HPC). Reference HPC mixtures (M_{1F}, M_{1S}, M_2 and M_3) designed for a 28-day minimum cube compressive strength of 70 N/mm^2 (MPa) were examined for the effect of SAP grain size, content and binder type on the above stated properties. Wedge splitting test was carried out on 100 mm cube specimen of HPC containing varied SAP contents (0.2, 0.3 and 0.4 by weight of binder (b_{wob})) and SAP sizes, cured by water immersion for 28, 56 and 90 days respectively. The results obtained was plotted as splitting force (F_{sp} in kN) against the crack mouth opening displacement (CMOD in mm) for computing the work of fracture (W_f), which is the area under the F_{sp} - CMOD curve. The study concludes that the splitting tensile strength and fracture energy of the HPCs are not directly affected by SAP addition (i.e. neither grain size nor content).

1   Introduction

High performance concrete (HPC) is defined by ACI (1999) as concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practice ([1]. It is a type of concrete specially designed to meet a combination of performance and requirements which specifically includes high strength or high early strength, durability and high elastic modulus [2, 3]. Its application includes precast pylons, piers and girders of many long span bridges in the world; tunnels, tall and ultra-high buildings; shotcrete repairs, poles, parking garages and agricultural applications [2]. The production involves high contents of fines (i.e. cement and other pozzolanic materials) and admixtures requiring good proportioning and handling towards achieving good workability, curing needs and other specific performance requirements. This type of concrete is however known to be susceptible to autogenous-shrinkage-caused-cracking which superabsorbent polymers (SAP) incorporation as an internal curing (IC) agent in HPC is reported as an effective approach to mitigate. SAP's created micro-voids however are arguably believed to be detrimental to the mechanical properties especially the fracture tendencies of the concrete.

The fracture energy G_F (N/m), defined as energy required for propagating a tensile crack of unit area is recommended to be determined from related tests with axial tensile strength adjudged most appropriate [4]. The factors influencing fracture energy (G_F - values) of normal strength concrete as highlighted in literature are water/cement (W/C) ratio; maximum aggregate size, age of concrete, curing condition, and size of structural members [5, 6, 7] . The same factors' influence on fracture energy applies to HPC but at a smaller magnitude. Hansen, *et al.,* [8] argue that aggregate type and content seem to have the greatest influence on fracture energy of HPC as a phenomenon caused by transition from interfacial fracture to trans-aggregate fracture.

ICCRRR 2018 with focus on the increasingly important aspect in modern infrastructure provision and retention (i.e. appropriate repairs, maintenance, rehabilitation, and if necessary retrofitting) of existing infrastructure with a view to extending its life and maximizing its economic return, hereby presents an opportunity for disseminating outcomes of recent study on SAP incorporation in HPC and the influence on its fracture properties. This paper hereby reports on the experimental study of the influence of varied SAP grain sizes and contents on the splitting tensile strength and fracture energy of HPC of varied binder combination types, water/binder (W/B) and curing age. The modified

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wedge splitting test setup – an approach for obtaining nonlinear fracture mechanics parameters based on [9] was adopted with two wedges pressed symmetrically between four roller bearings in order to split the specimen into two halves.

2 Experimental procedure

2.1 Materials

The materials used for the study are SAP, natural sand, crushed greywacke stone, cement (CEM I 52.5 N), silica fume (SF), Fly Ash (FA), Corex Slag (CS), water and superplasticiser. Two grain sizes of SAP (SP_1 and SP_2 as described in earlier publication [10] at varied SAP contents (0%, 0.2%, 0.3% and 0.4%) by weight of binder (b_{wob}) were used for the study. The SAP is a thermoset polymer, specifically covalently cross-linked polymer of acrylic acid and acrylamide, obtained from bulk solution polymerisation and neutralised by alkali hydroxide, which according to Schrofl *et al.*, [11] have been proven efficient as internal curing agent in concrete. The absorption capacity determined by tea-bag test as reported in [12] is 250 g/g in distilled water and 25 g/g in cement pore solution (CPS) for both the SP_1 and SP_2. The SAP particles were stored (with exposure to moisture prevented) in as received sealed plastic bag inside a wooden cupboard until use.

CEM I 52.5 N supplied by PPC, South Africa conforming to [13, 14] served as the main binder. SF, by SiliconSmelters of the FerroAltantica group; FA from AshResources and CS supplied by PPC; all in powdered form were used as SCM for the various HPC mixtures as required by the mix design. The blends of the binders were categorised into three binder types (1, 2 and 3): Binder types 1 – a combination of CEM I 52.5 N and SF (7.5% b_{wob}), also referred to as binary cement and adopted for reference HPC mixtures M_2 (0.25 W/B) and M_3 (0.30 W/B); Binder Type 2 – which composed of CEM I 52.5 N, SF (7.5% b_{wob}) and FA (17.5% b_{wob}) used for M_{1F} (0.2 W/B); and Binder Type 3 – made of CEM I 52.5 N, SF (7.5% b_{wob}) and CS (17.5% b_{wob}) used for M_{1S} (0.2 W/B). Binder Types 2 and 3 are referred to as ternary cements. The details of the mix constituents for the reference HPC mixtures made with the respective binder types is presented [10].

The Natural sand used had minimum particle size of 300 μm (i.e. all the particles smaller than 300 μm removed using the sieving method) in compliance with requirement for fine aggregate specification for HPC production [3, 15, 16]. The sand has the following physical characteristics: Fineness Modulus – FM = 2.79, Coefficient of uniformity – C_u = 2.43, Coefficient of curvature – C_c = 1.02 and dust content = 0.3%. This conforms to medium sand classification according to

[17]. 13mm crushed greywacke stone served as coarse aggregate in compliance with typical HPC mixes found in literature [3, 16, 18]. The crushed stone was washed and spread in the open air for surface drying before measuring the required quantity for particular reference HPC mixture production. This was to reduce the dust content of the coarse aggregate in order to achieve low water demand for the HPC mixtures, especially the M_{1F} and M_{1S} with extremely low W/B.

2.2 Methods

Splitting tensile strength and fracture energy for the HPC mixtures were determined through the modified wedge splitting test approach based on the works of [9, 19] . The specimen for the wedge splitting test was cast with a 30 mm x 20 mm groove introduced by insertion of a wooden block and cured in the water-bath. It was further notched to 50 mm depth from the cube specimen bottom (Figure 1 (b)) at the required curing ages (28, 56 and 90 days) and an epoxy glue was used to attach PVC clips (Figure 1 (a)) fabricated to hold LVDTs at the groove edge for a measurement of the CMOD during the test. The test setup developed as shown in Figure 1 (c) using a loading assembly (14 ° wedge plate welded to IPE 160 I-section (160 x 82 x 15.8 kg/m^3 I-section)) made to move within two Ø25 mm needle roller bearings (NKI 25/30) attached to the sides of fabricated steel frame (made of C-channels) for a transfer of the vertically applied load to horizontal loading on the cube specimen.

The cube was placed on a base plate with two 10 mm diameter bars welded to it (for stability) as observed in [20, 21] to induce crack opening from the notched groove-end of the wedge splitting specimen instead of the single bar centrally placed specified in [9, 19] . This is to ensure stability of the cube specimen during testing. An interlayer of 4 mm thick hardboard of 8 mm width was placed on the 10 mm diameter bars on the base plate (as shown in Figure 1 (d)) to prevent direct transfer of axial force from the base when carrying out the wedge splitting test.

The load was applied at a crack mouth opening rate of 0.1 mm/min in a closed loop servo control machine (Instron 50 kN actuator by Instron Ltd.) having maximum loading capacity of 50 kN (dynamic) / 62.5 kN (static). The crack opening displacement (COD) was measured on the specimen with two LVDTs attached using the plastic holders (Figure 1 (a)) connected directly to the Instron machine ensuring crack opening control of the test set up and a direct data transfer to a dedicated computer. A total of 288 (100 mm) cube HPC samples were studied for splitting tensile strength and fracture energy. An average of the three tests per specific sample gave the values reported in this work.
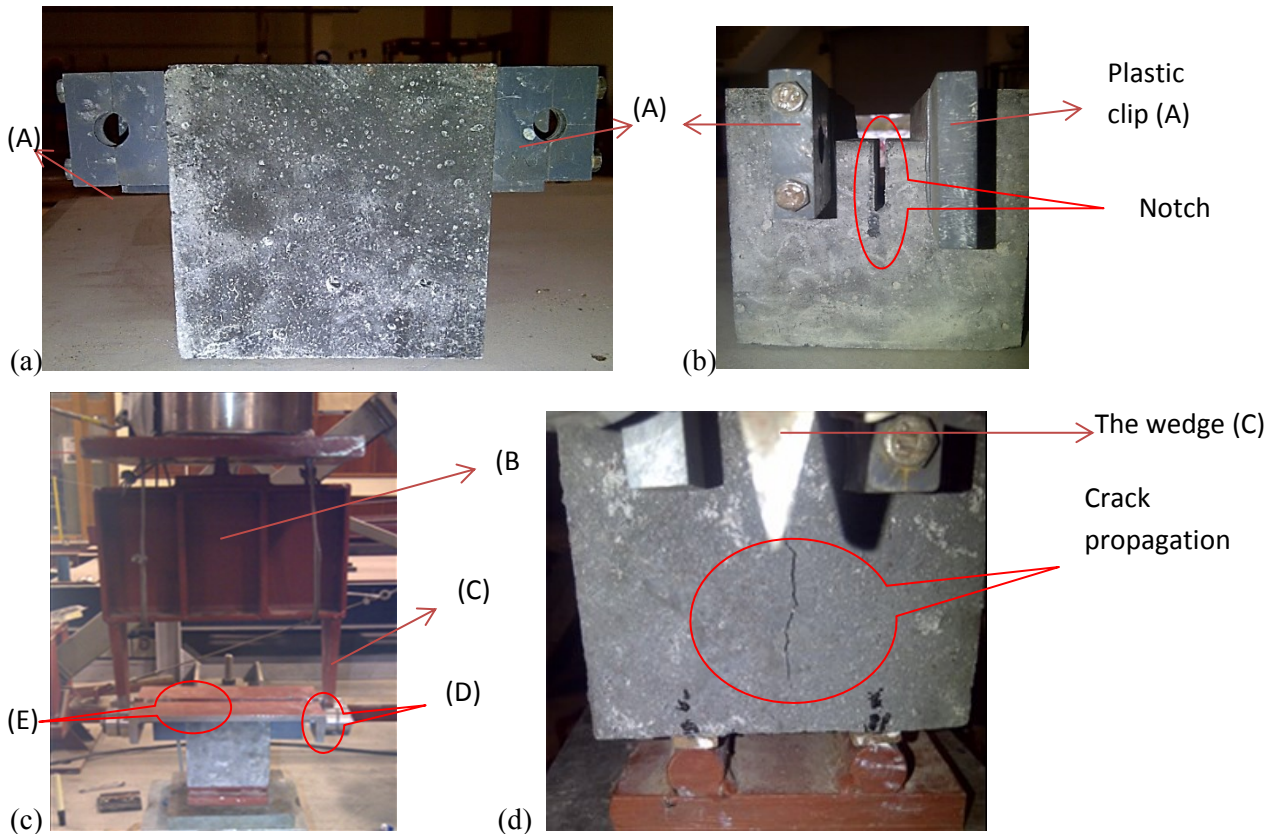
Fig 1: Test setup for wedge splitting test – (a) shows the plastic clip (LVDT holder) glued to concrete specimen; (b) the groove (30mm x 20mm) and notch (20 mm deep); (c) the complete wedge splitting setup and (d) the crack propagation on the cube specimen.

*Note that the label (A) in Figure 3above is plastic clip; (B) is the IPE 160 I-section; (C) is the metal wedge; (D) is the two Ø25 mm needle roller bearings and (E) is the fabricated steel frame (made of C-channels).

3   Results and discussion

3.1   Results

The results extracted from the test setup as explained earlier was the splitting force (F_{sp} in kN) against the crack mouth opening displacement (CMOD in mm). Figure 1 shows a typical set of results for triplicate specimen (for $M_{1S}SP_1$-0.4 after 28 days curing).

The data obtained was then computed for each sample for calculation of the work of fracture (W_f) which is the area under the F_{sp} - CMOD curve using the trapezoidal rule in accordance to [19, 9] recommendations and hence the calculation of the fracture energy (G_F). Figures 3 to 6 presents the plots of fracture energy against curing age for the respective HPC mixtures while the detailed results for the fracture energy as required by [9] with values of the cube compressive strength ($f_{c,cube}$), E-modulus (E_c) and the Splitting force (F_{sp}) provided can be found in [22] – Tables 5.12 & 5.13.

An assessment of the results reveals no particular trend on influence of SAP addition on the splitting tensile strength and fracture energy of the HPCs. The

works of [23] reported similar or higher splitting tensile strength for SAP modified concretes on the 28 days.
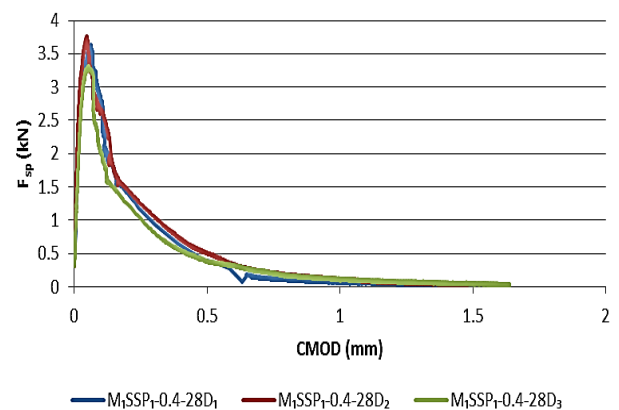

Fig 2: Typical plot of data extracted from Wedge Splitting Test for W_f and G_f Calculation

The explanation offered for the better splitting tensile strength at 28 days in SAP modified concrete by [24] is that SAP, in parallel to shrinkage mitigation, successfully increased the tensile cracking resistance of the cement-based system. This explanation is applicable in this test too as the reason for no significant reduction in tensile splitting strength of the SAP modified HPC.
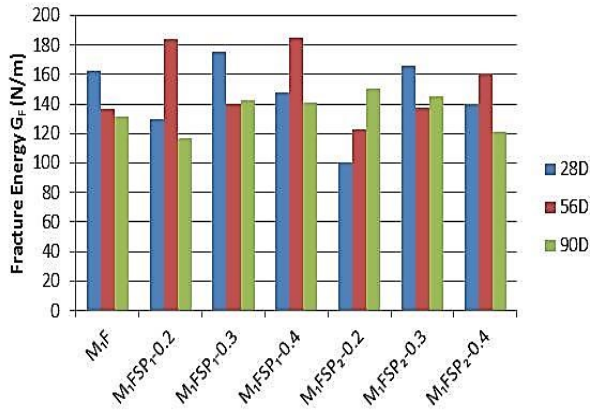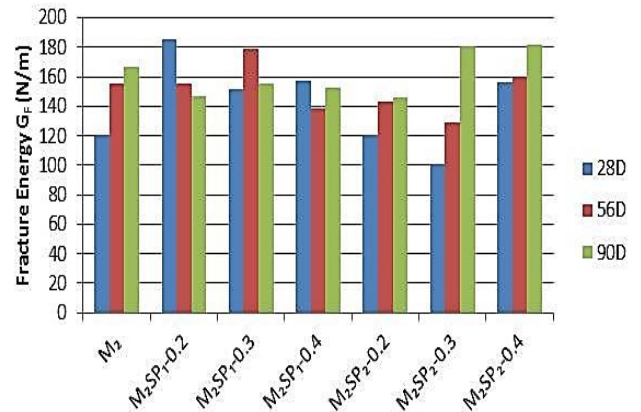
Figure 3: Fracture Energy (G$_F$) of M$_{1F}$

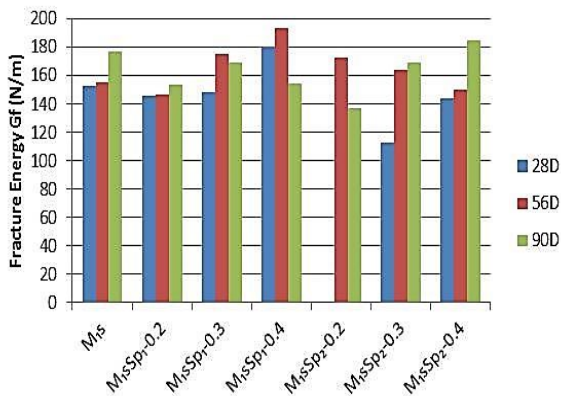

Figure 5: Fracture Energy (G$_F$) of M$_2$

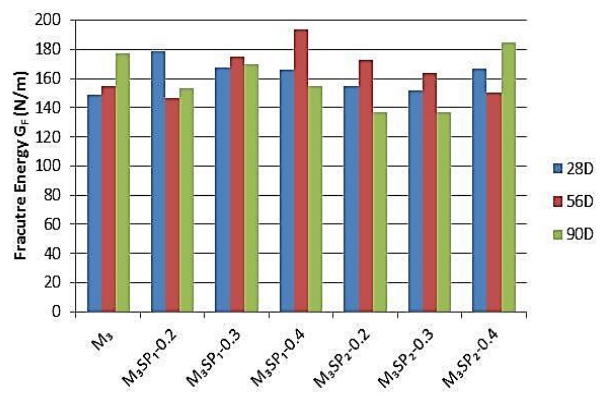**Figure 4: Fracture Energy (G$_F$) of M$_{1S}$**

Figure 6: Fracture Energy (G$_F$) of M$_3$

The fracture energy values are generally within the same range of 130 N/m to 185 N/m for all specimens with or without SAP addition except in a few instances which deviates from the range. The G$_F$ value obtained is within the expected range for concrete of this strength range made from maximum aggregate size of 13 mm [4]. A check of the G$_F$ in line with MC 2010 provision on basis of maximum aggregate size (G$_F$ = a. Θ^n) gave 183.15 N/m while a second check using a characteristic compressive strength of 90 N/mm^2 (using $G_f = 72.f_{cu}^{0.18}$) gave a value of 161.85 N/m. Both checks therefore show that G$_F$ values obtained are similar to the MC 2010 [4] provisions. The result for the 28 day test for M$_{1S}$SP$_2$-0.2 sample was however lost as the samples failed suddenly during testing due to poor closed loop control.

Figures 3 to 6 shows that curing age influence on the G$_F$ values cannot also be placed into any particular trend. The splitting force was also observed to generally maintain a value range of 3.0 kN to 5.0 kN for all the HPCs examined except two cases of inconsistencies. There was however cases of observed reduction in the value of G$_f$ with decrease in age (Figure 3, M$_{1F}$ and M$_{1F}$SP$_1$-0.2)

It is observed that three variables (W/B, SAP grain size and SAP content – asterisks' (*[1]), Table 1) in that order had significant effect individually on the force of splitting. W/B showing the highest influence is as expected, since higher W/B in concrete should infer lower force required to split the concrete specimen. The two variable interactions further affirm the influence of

SAP content and SAP type when combined with binder type on the splitting force of the HPC containing SAP.

Figure 7 show that the mean splitting force (from the statistical analysis) has a negative correlation with SAP content. The splitting force (and hence the splitting strength) decreases as the SAP content increases. The widest scatter of splitting force value was noted to be in the reference mixtures, an indication of the greater influence of W/B on the varied splitting force obtained for reference HPC mixtures. Figure 7 further shows that SP$_2$ inclusion in HPC resulted in lower splitting force than SP$_1$. The splitting force of HPC containing SP$_1$ was similar to that of the reference mixtures.

The results of general linear – univariate analysis (using SPSS 22) of fracture energy of the HPC with SAP as presented in Table 1 reflect that binder type, SAP type and SAP content (asterisks (*[1]), in this decreasing order) has significant individual effect on the outcome of fracture energy, while the effect of W/B is not significant as a single factor. At two variable combinations level, SAP type combined with binder type has the least significant effect. Influence of combinations of W/B*curing age, SAP type*curing age and binder type*curing age (asterisks (*[2])) are noted to be very significant at the two factor analysis level.

Three and four factor analysis however affirmed the postulation that binder type is the more influential factor than the W/B in combination with the three other variables (SAP content, SAP type and curing age).

Figure 8 shows a plot of the G_F of the HPC mixtures against SAP contents as influenced also by the binder type. The figure shows that the fracture energy of the HPCs increases slightly with increasing SAP contents. The HPCs with the highest SAP content has the highest mean fracture energy, followed closely by the reference mixtures. This implies that although the splitting force was higher at lower SAP content, the ductility of the HPC increases as the SAP contents increase. The ternary binders (Type 2 and Type 3) were generally observed to show better scatter than the binary binders (Type 1).
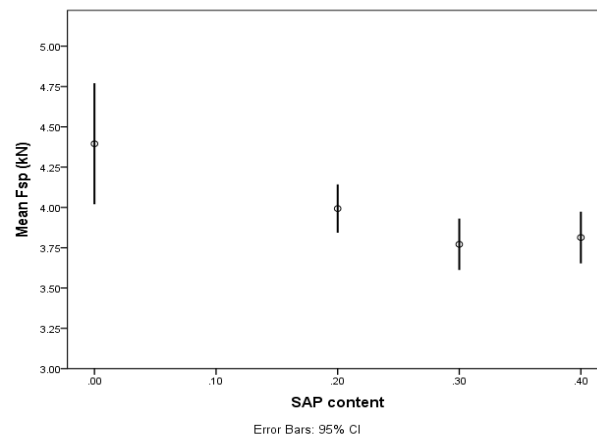

Fig 7: Mean Splitting Force (F_{sp}) vs, SAP content

Table 1: Tests of Between-Subjects Effects for Splitting Force (F_{sp})

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	69.768[a]	82	.851	3.401	.000
Intercept	2794.699	1	2794.699	11171.046	.000
Single factor Analysis					
W/B	11.774	1	11.774	47.064	.000*[1]
SAP content	1.642	2	.821	3.281	.041*[1]
SAP type	2.314	1	2.314	9.250	.003*[1]
Binder type	.015	1	.015	.058	.810
Curing Age	.791	2	.395	1.580	.210
Two Factor Analysis					
W/B * SAP content	.616	2	.308	1.230	.296
W/B * SAP type	.028	1	.028	.110	.740
W/B * Curing Age	.018	2	.009	.036	.964
SAP content * SAP type	.097	2	.048	.193	.824
SAP content * Binder type	1.929	2	.964	3.855	.024*[1]
SAP content * Curing Age	.497	4	.124	.496	.739
SAP type * Binder type	5.658	1	5.658	22.617	.000*[1]
SAP type * Curing Age	.621	2	.310	1.241	.293
Binder type * Curing Age	.235	2	.118	.470	.626
Three Factor Analysis					
W/B * SAP content * SAP type	.670	2	.335	1.339	.266
W/B * SAP content * Curing Age	.420	4	.105	.420	.794
W/B * SAP type * Curing Age	.912	2	.456	1.822	.166
SAP content * SAP type * Binder type	.268	2	.134	.536	.586
SAP content * SAP type * Curing Age	1.621	4	.405	1.620	.174
SAP content * Binder type * Curing Age	2.024	4	.506	2.022	.095
SAP type * Binder type * Curing Age	.043	2	.021	.085	.918
Four Factor Analysis					
W/B * SAP content * SAP type * Curing Age	.966	4	.241	.965	.429
SAP content * SAP type * Binder type * Curing Age	1.307	3	.436	1.741	.162
Error	30.521	122	.250		
Total	3271.795	205			
Corrected Total	100.289	204			

a. R Squared = .696 (Adjusted R Squared = .491)

Table 2: Tests of Between-Subjects Effects for Fracture Energy

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	86050.548[a]	82	1049.397	2.620	.000
Intercept	3867589.069	1	3867589.069	9654.943	.000
Single Factor Analysis					
W/B	220.069	1	220.069	.549	.460
SAP content	3812.275	2	1906.137	4.758	.010*[1]
SAP type	2914.238	1	2914.238	7.275	.008*[1]
Binder type	3139.936	1	3139.936	7.838	.006*[1]
Curing Age	963.080	2	481.540	1.202	.304
Two Factor Analysis					
W/B * SAP content	607.826	2	303.913	.759	.471
W/B * SAP type	1199.360	1	1199.360	2.994	.086
W/B * Curing Age	5085.954	2	2542.977	6.348	.002*[2]
SAP content * SAP type	402.668	2	201.334	.503	.606
SAP content * Binder type	392.120	2	196.060	.489	.614
SAP content * Curing Age	1779.739	4	444.935	1.111	.355
SAP type * Binder type	68.479	1	68.479	.171	.680
SAP type * Curing Age	11191.428	2	5595.714	13.969	.000*[2]
Binder type * Curing Age	4629.895	2	2314.947	5.779	.004*[2]
Three Factor Analysis					
W/B * SAP content * SAP type	3315.301	2	1657.650	4.138	.018*[3]
W/B * SAP content * Curing Age	1863.591	4	465.898	1.163	.331
W/B * SAP type * Curing Age	604.438	2	302.219	.754	.472
SAP content * SAP type * Binder type	536.823	2	268.411	.670	.514
SAP content * SAP type * Curing Age	1111.548	4	277.887	.694	.598
SAP content * Binder type * Curing Age	4928.443	4	1232.111	3.076	.019*[3]
SAP type * Binder type * Curing Age	931.425	2	465.713	1.163	.316
Four Factor Analysis					
W/B * SAP content * SAP type * Curing Age	1432.025	4	358.006	.894	.470
SAP content * SAP type * Binder type * Curing Age	5918.920	3	1972.973	4.925	.003*[4]
Error	48069.747	120	400.581		
Total	4857480.375	203			
Corrected Total	134120.295	202			

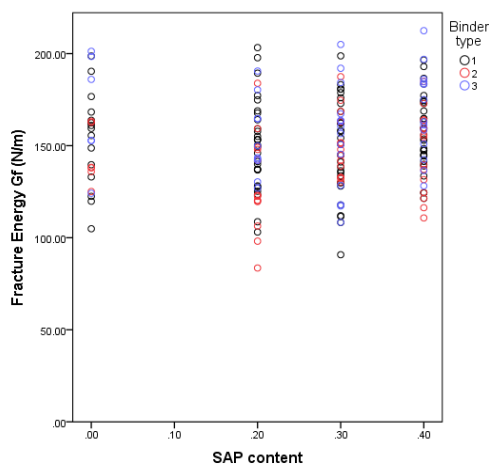a. R Squared = .642 (Adjusted R Squared = .397)

Figure 8: Gf vs. SAP contents as influenced by binder type

4 Conclusion

The findings of the experiment conducted in this research hereby concludes that AP addition within the limits of the contents used in this study (0.2 to 0.4% b$_{wob}$) in low W/B HPCs has no significant influence on the elastic and fracture properties of the concrete. Although the splitting force was slightly higher at lower SAP content, the ductility of the HPCs increased as the SAP contents increase, the most significant of the factors studied on the fracture properties is the binder type.

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