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Early-age and long-term strength development of high-performance concrete with SAP

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HIGHLIGHTS

- Early-age and long-term compressive strength of low W/B HPC with SAP as IC-agent was investigated.
- 70 MPa as minimum strength were studied with 25 g/g extra water provided for SAP absorption.
- Variables considered are SAP content, size, binder type, w/b ratio and curing age.
- Compressive strength of HPC slightly decreased with increase in SAP content.
- SAP's absorption into Power's Model shows compatibility for prediction of strength development.

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ABSTRACT

Internal curing of high-performance concrete (HPC) by the addition of Superabsorbent Polymers (SAP) has been proven to be effective in mitigating autogenous shrinkage. The issues of concern in research, however, is the extent to which strength development is impacted by the voids created by SAP as cement hydrates with age. In this study, the influence of SAP content, size, binder type, water/binder ratio (W/B) and curing age on the early-age and long–term strength development of a low W/B HPC was examined. HPC mixtures designed for a minimum 28-day target cube strength of 70 MPa (i.e. C55/67 – C100/115) were studied with 25 g/g extra water provided for SAP absorption. Mortar (50 mm) and concrete (100 mm) cubes were cast and cured in water for different hydration periods. The results reveal that the compressive strength of the HPC mixtures decreased slightly (both for the early-age and long-term) as SAP content increased. Statistical examination of the results further revealed that W/B and SAP contents significantly influenced the strength development while a simulation of the SAP's water absorption into Powers' Model show compatibility for prediction of strength development trends in HPC with SAP.

1. Introduction

The growing trend in the utilisation and adoption of high-performance concrete (HPC) and ultra-high–performance concrete (UHPC) in the construction industry, and the susceptibility of these types of concrete to self-desiccation and autogenous shrinkage has called for concerted efforts on improved curing methods. Internal curing (IC) of concrete is seen as an adaptable measure, since curing by complete immersion in water of concrete elements – which does not address the issue of autogenous shrinkage, is impracticable in real site situation. This has necessitated the intensive study of the IC-agents being introduced in concrete. Any material used as an IC-agent ought to be of the appropriate type and optimum proportion. At the same time, its addition should not result in any detrimental effect on the required properties of the concrete. Pre-soaked lightweight aggregates (LWA) and superabsorbent polymers (SAP) are the most acceptable IC-agents [1,2]. Furthermore, SAP has been identified of these two to be the most appropriate and promising IC-agent in concrete [3,4].

SAP is a general term used to describe polymers that can retain large amounts of water. They are cross-linked polyelectrolytes which start to swell upon contact with water or aqueous solutions, resulting in the formation of a hydrogel [3]. The two main categories of SAPs are thermoplastic polymers (or linear polymers)

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and thermoset polymers (or cross-linked polymers). Thermoplastic polymers are noted to be of high molecular weight, having overlapping polymer chains with the junctions acting as physical cross-links, which form pseudo-three dimensional structures. Thermoset polymers, on the other hand, are three-dimensional polymer networks with chemical cross-links which hold polymer chains together, thus preventing their being dissolved when soaked in solvents [4]. The thermoset polymer has been adopted for this study; specifically, the covalently cross-linked polymers of acrylic acid and acrylamide, neutralised by alkali hydroxide which, according to [3], have been proven to be efficient as IC-agents in concrete.

Research on the incorporation of SAP in cement mortar or concrete has been reported with diverse opinion in the literature. While some studies [5–7] have observed that the incorporation of SAP in cement mortar resulted in long-term strength increases or no adverse effect, others [8–11] have reported a decrease in strength. Considering that previous studies [5–15] have recommended further works on the influence of SAP as an IC-agent, this study examines the effect of SAP grain sizes on compressive strength, being an essential property of concrete. The compressive strength of concrete containing SAP as an IC-agent is generally dependent on the curing conditions, age and material composition [3].

Esteves *et al.* [12] found that when the relative humidity during curing was 95%, the compressive strength of mortar with 0.2% SAP addition declined by 15–20%. However, when the humidity was 30%, the decline in compressive strength was only 5%. Craeye & De Schutter [13] reported a compressive strength reduction of concrete containing silica fume - SF (0.32 water:binder (W/B)) at different SAP contents (with an estimated SAP absorption capacity of 134 g/g). The compressive strength reduction was noted to be very pronounced at higher SAP dosages and contents of entrained water (W_e). Another experiment conducted in the same laboratory [14] with another type of SAP (with an estimated absorption capacity of 45 g/g) showed a similar significant reduction in the 28-day compressive strength. These two studies [13,14] were, however, believed to have overestimated the SAP absorption capacity and thus added too much water into the concrete leading inevitably to the compressive strength reduction [3,15]. With a range of W/B between 0.35 and 0.50, Hasholt *et al.* [15,16] investigated the compressive strength of concrete with varying proportions of SAP content ranging between 0% and 0.6%. All the samples were cured in water up to 28 days. These studies modelled the effect of SAP on the concrete compressive strength by combining Bolomey's formula and Power's model. They observed that the net impact of SAP (negative or positive) depends on the mix design and curing age. The studies concluded that SAP has little effect on hydration and hence leads to reduced compressive strength when the W/B is high (>0.45), especially at early ages and with large SAP additions. However, Hasholt *et al.* [16] have opined that concrete specimens with a low W/B and low SAP addition exhibit compressive strength increases at later ages.

Ding *et al.* [17] studied the factors influencing the strength of concrete containing SAP at two W/B (0.37 and 0.3) using SAP particle sizes that ranged between 50 and 100 μm. Adequate arrangement was made for the sorption capacity of SAP based on the Power's Model with focus on 3, 7 and 28 days age. The study reported that the compressive strength of SAP-incorporated concrete was found to be influenced by the w/c ratio, SAP dosage and particle size. and that The three influencing factors can be ranked in the decreasing order of their degrees of influence as water–cement ratio > SAP dosage > particle size. The study [17] concluded that lower w/c ratio was more beneficial for improving the early age strength of concrete and that when the SAP particle size was relatively large, it was easier to improve the early-age compressive strength of SAP-incorporated concrete. However, the particle size had a negative correlation with the 28-day strength.

The recommendations of RILEM TC260-RSC [18] stated that the dosage of SAP necessary for mitigating autogenous shrinkage depends on their properties, especially the sorption capacity in cement pore fluids based on the round-robin tests conducted [19,20]. It was deduced that the sorption capacity of SAP applicable to IC in concrete is usually within the range of 10–30 g/g of pore solution per gram of SAP. SAP particles below 350 um are considered the most suitable as IC-agent in concrete. The RILEM TC260-RSC recommendation [18] asserts that iterative procedure should be applied, for a trade-off between limiting autogenous shrinkage and any possible negative impact on important concrete properties, e.g., workability or strength. Temperature range of 10–30 °C (same as the temperature at which concrete mixing is performed) was recommended for negligible effect on the sorption capacity of SAP. A possible adverse effect of SAP inclusion in concrete was highlighted in [18] as the reduction in workability, especially when the water absorbed by SAP is not adequately accounted for. A situation where SAP is added to the concrete without changing its total W/B will lead to a decrease in the basic W/B and thus reduce the water available as mixing water. The influence of SAP on the mechanical properties was, however, reported in [18] to be both negative and positive. It, therefore, recommends the need to check the negative effect of SAP on workability, pumpability and air content in the fresh sate, while the mechanical properties and durability characteristics are to be assessed in the hardened state. It was offered as a general rule in [18] that if the changes in mechanical properties of concrete when SAP is added, with appropriate account made for its sorption capacity by additional water, do not exceed those induced by the increased W/B without addition of SAP, the net effect of SAP can be assumed as negligible [19]. Concrete mixes with W/B lower than 0.4 (i.e. HPC and ultra-high-performance concrete (UHPC)) are noted in [18] to experience high self-desiccation, and autogenous shrinkage and therefore require the inclusion of SAP as an IC-agent.

The works of Hasholt et al. [15,16] and Ding et al. [17], though attempted to study concrete with w/c less than 0.4, the concrete mixtures did not incorporate supplementary cementitious materials (SCMs). The addition of SCMs to conventional concrete can influence SAP's effectiveness as an IC-agent. It is, therefore, necessary to study the influence of SAP as an IC-agent on the compressive strength development of low W/B HPCs (0.2–0.3)containing different supplementary cementitious materials in addition to silica fume (SF). These materials are requisites towards the achievement of such type of concrete as a further step to the submissions of Hasholt *et al.* [16] and Ding *et al.* [17].

This paper, therefore, examines the effect of SAP on the early-age and long-term compressive strength of HPC with W/B ranging from 0.2 to 0.3 and having a minimum 28-day strength of 70 MPa (i.e. C55/67–C100/115). The influences of SAP size, content and binder type were examined to ascertain which of these variables would significantly impact on the concrete's compressive strength development. The results and discussion in this study provide a reasonable basis for the efficient specification of SAP for use in the HPC of low W/B ratio (0.2–0.3). It also offers a basis for the prediction of the compressive strength development at ages beyond the 28 days as required for HPC according to the postulations of some authors [21,22].

2. Experimental investigation

2.1. Materials

The materials used for the study are SAP, natural sand, crushed stone with a nominal size of 13 mm, cement (CEM I 52.5 N), silica fume (SF), Fly Ash (FA), Corex Slag (CS) which is ground granulated slag produced through the smelting reduction process (called corex process) as a more environmentally friendly than blast furnace process, water and superplasticiser (Chrysol Premia 310 – a PCE). Section 3.1 presents details of the oxide composition of the cementitious materials. Two grain sizes of SAP (SP_1 ($\leq$300 μm) and SP_2 ($\leq$600 μm)) as described in [23] at varied SAP contents (0%, 0.2%, 0.3% and 0.4%) by weight of binder (b_{wob}), were used. The SAP is a thermoset polymer, specifically, a covalently cross-linked polymer of acrylic acid and acrylamide. It was obtained from bulk solution polymerisation and neutralised by alkali hydroxide, which according to [24] have been proven efficient as an IC-agent in concrete. The absorption capacity determined by a tea-bag test as earlier reported in [25] (Table A-1, the Appendix) 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 absorption capacity result of the SAP particles obtained through the tea-bag test for CPS in this study agrees well with the 10–30 g/g reported in the literature [3,18,19] for this type of SAP. The SAP particles were stored (with exposure to moisture prevented) inside a wooden cupboard until used as received in a sealed plastic bag in-line wth the recommendations of [18].

The natural sand used had a minimum particle size of 300 μm (i.e. all the particles smaller than 300 μm removed using the sieving method) in compliance with the requirement for fine aggregate specification for HPC production [21,22,26]. The sand sample 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 = 0.31%. Figure A-1 and Table A-2 in the Appendix present details of available fine aggregates (and their blends) from which the sieved natural sand (SN_1) was chosen for use in this study. This conforms to medium sand classification according to [27]. 13 mm crushed Greywacke stone served as coarse aggregate in compliance with typical HPC mixes found in the literature [21,22]. Greywacke stone is a textured sedimentary rock variety of sandstone in Paleozoic strata and characterized by its hardness, dark colour, and poorly sorted angular grains of quartz, feldspar, and small rock fragments or lithic fragments set in a compact, clay-fine matrix. 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 to achieve low water demand for the HPC mixtures, especially the mixtures containing FA (M_{1F}) and CS (M_{1S}) with extremely low W/B.

CEM I 52.5 N conforming to [28,29], served as the main binder. The blends of the binders were categorised into three types (Type 1 - binary cements (M_2 & M_3); Types 2 and 3 - ternary cements (M_{1F} and M_{1S}), as presented in Table 1.

The details of the mix constituents for the reference HPC mixtures made with the respective binder types is presented in Table 2.

2.2. Methods

Four reference HPC mixtures of different binder combination types (Table 1) with a minimum 28–day characteristic strength of 70 MPa (i.e. C55/67 – C100/115 HSC) were used (Table 2). The mixtures were designed using Aitcin (1998) reference method for HPC mixtures. Furthermore, other HPC mixtures having varied SAP contents (0.2%, 0.3% and 0.4%) for the two SAP sizes (SP_1 and SP_2) were made from the reference HPC mixtures, with extra water provided for SAP absorption based on 25 g/g determined using the tea-bag test. The tea-bag test remains the most adopted method for SAP absorption by researchers and also one of the two methods recommended by [19] despite its shortcoming, as noted in [25]; this is due to its simplicity and ease of use in a typical laboratory setting.

Table 1
Binder types and composition.

Binder	Composition	Specimen designation and W/B
Type 1	CEM 52.5 N (92.5%) + SF (7.5% b_{wob})	M_2 (0.25 W/B) and M_3 (0.30 W/B)
Type 2	CEM 52.5 N (75%) + SF (7.5% b_{wob}) + FA (17.5% b_{wob})	M_{1F} (0.2 W/B)
Type 3	CEM 52.5 N (75%) + SF (7.5% b_{wob}) + CS (17.5% b_{wob})	M_{1S} (0.2 W/B)

The concrete production process involved first adding the fine aggregate to a 50L capacity pan-mixer. This is followed by the binders which had first been thoroughly hand-mixed to enhance even dispersion of the SF and the other SCMs (FA or CS as appropriate) until a uniform colour was observed. After mixing for about 30 s, the dry SAP particles were added and all the fine contents mixed for another 30s (this was to enhance proper dispersion of the SAP particles). The coarse aggregate was added, and mixing continued for another one minute. Thereafter, water, already mixed with superplasticiser (Chryso fluid Premia 310 – a PCE), was added and the mixing was then allowed to continue for another 3 mins as recommended in the literature [22,26,30].

Slump flow measurement was carried out using the flow table test (described in [31]) as a measure of workability of the HPC mixtures. At the same time, both the room and concrete temperature were also measured using a digital pocket thermometer (Checktemp 1, Model No. H1- 740,024 by HANNA Instruments Incorporated). After ascertaining that the mixture met the required workability and cohesion (400 – 600 mm slump flow spread) for the specified design mix, specimens for both early-age and long-term strength tests were prepared as explained in Sections 2.2.1 and 2.2.2. The cast concrete specimens were covered in the laboratory with thick polythene sheets and allowed to harden for 24 h before demoulding and curing in a water bath at 20 ± 3 °C until testing.

2.2.1. Early-age strength development

The early-age strength test was conducted using sieved mortar samples extracted from the fresh HPC mixtures using a 4.75 mm sieve. 50 mm cube mortar samples were cast and crushed after different curing ages (i.e. 24 hrs, 48 hrs, 72 hrs and 7 days) to assess the early-age strength development of the HPC with SAP. M_2 and M_{1S} specimens contain both SP_1 and SP_2 while M_3 and M_{1F} have only SP_1. Triplicate samples of the 50 mm cubes per test were examined for each independent variable.

2.2.2. Long-term strength development

A total of 384 cubes (100 mm) based on a 2 × 3 × 4 × 4 × 4 factorial experimental design (i.e. two SAP sizes, triplicate samples, four reference mixes, four SAP contents and four curing ages) was adopted for this test. Specimens were tested for compressive strength on the 7, 28, 56 and 90-day. Furthermore, the demoulded density and total porosity were measured. The demoulded density (dmd) was determined by dividing the direct weight of the demoulded concrete with the measured volume of individual concrete cube. The density value at a specific curing age was then taken as the average of three specimens for that age. At the same time, porosity was determined by dividing the average density for specified age by the average of the demoulded densities for all the twelve specimens of an HPC mixture. The total porosity was then determined using Eqn. (1).

$$\text{Totalporosity} = \frac{dd - dmd}{dd} X100 \tag{1}$$

Table 2
Mix constituents of HPC mixtures.

Constituents	Reference Mixes (kg/m^3)			
	M_{1F}	M_{1S}	M_2	M_3
Water	125	125	134	155
Cement	530	530	540	500
Coarse Aggregate	1050	1050	1050	1050
Sand	590	590	710	700
Fly Ash	122.5	0	0	0
Corex Slag	0	122.5	0	0
Silica Fume	52.5	52.5	40	40
Superplasticiser (Chryso Premia 310)	21	21	16	5.4
Water/binder	0.2	0.2	0.25	0.3

where *dd* is the designed density for HPC with SAP, arrived at by the addition of the weight of SAP and extra water added for SAP absorption to the initial calculated weight in kg/m^3 for the reference mixture.

The compressive strength test was performed following the requirement of [30–34]. The test setup is shown in Fig. 1. The mortar and concrete cubes were tested using the Contest Materials Testing machine of 2000 kN maximum loading capacity ensuring the face in touch with the loading platens are not same as the cast face of the cube. The load was applied at a rate of 0.1 N/mm^2 on the specimen as specified in [34].

3. Results and discussion

3.1. Oxide composition of cementitious materials

Table 3 presents the oxide composition of the cementitious materials. CEM I 52.5 is 68.6% CaO, 17.5% SiO_2 and 3.18% Al_2O_3. The SF has SiO_2 to be 77.9%, Fe_2O_3 (1.98%) and Al_2O_3 (0.53%) at a Silica:Sesquioxide ratio (SR) of 1.54 while the FA is next on SiO_2 content of 52.1%, Al_2O_3 of 29.9%, Fe_2O_3 of 3.81 at an SR of 0.56. The CS, on the other hand, is majorly CaO (45.6), with the SiO_2 content being 27.1%, Al_2O_3 of 12.4% and SR of 1.24. The SiO_2 content and SR values affirm the SF should be very reactive for liberating CaO from the PC, followed by FA while CS ranked lowest in this regard. The Si/Ca ratio might be an advantage for the CS with additional CaO contribution to the mixture matrix. The porous nature of CS and FA and the alkaline content are to be explored in M_{1F} and M_{1S} in binder Type 2 and 3 mixtures.

3.2. Early-age strength development

The results of the fresh properties reveal slump flow values of 450 to 580 mm (Table 4) – an indication that all the mixtures met the workability requirements (i.e. 400–600 mm slump flow spread as specified in Section 2.2). The result of the fresh properties, as shown in the Appendix (Tables A-3 and A-4) has been discussed in an earlier publication [36]. It revealed that the total W/B increases as the SAP content increases while the slump flow values, on the other hand, remain in the same range for all HPC mixtures (530 to 570 mm – M_2; 450 to 500 mm – M_3; 550 mm to 600 mm – M_{1F} and 450 to 500 mm – M_{1S}). The HPC mixtures containing FA (i.e. M_{1F}) is noted to be more flowable than the one containing CS (M_{1S}) even though they are of same W/B. This is an indication that the FA, known to be of good and distinct inter-particle spaces gave a better performance in enhancing improved workability of the low W/B HPC mixture. M_2 (0.25 W/B) is also more flowable than M_3 (0.30 W/B) due to its higher superplasticiser content.

Results of the test conducted for pH-values of the simulated CPS as presented in Table A-1 of the Appendix reveal that all the HPC mixtures have pH-values range of 12.4 to 13.0. This implies that they are all of high alkaline nature as expected of concrete. The M_2 mixture (at pH-value of 12.89) is the closest to the value for the CPS, W/C of 5.2 (at pH-value of 12.87) recommended for CPS from 0.42 water:cement ratio. The ternary cements [M_{1F} (at pH-value of 12.47) and M_{1S} (pH-value of 12.41)] are slightly less alkaline than CPS (W/C 5.2) but of similar value to that of W/C 2.5 (recommended for typical 0.2 water: cement ratio pore solution). The result for the ternary cements agrees well with pH-values for pore made from type II cements (usually CEM I blended with SCMs hav-

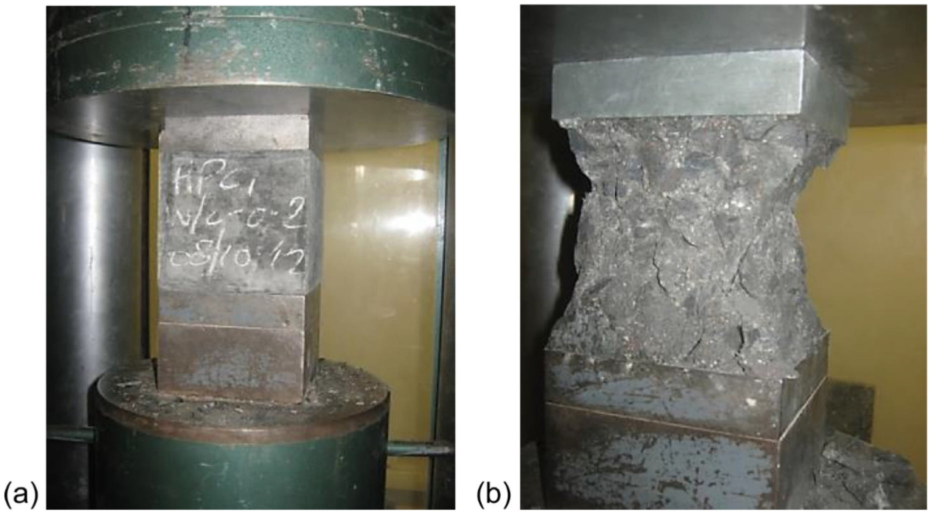

Fig. 1. Compressive strength test setup (a) before failure, (b) after failure.

Table 3
Oxide Composition of Cementitious Materials.

Oxide (%)	Cementitious Materials			
	CEM I 52.5 N	SF	CS	FA
Na_2O	0.45	1.78	0.00	0.40
MgO	0.97	1.67	9.52	0.97
Al_2O_3	3.18	0.53	12.37	29.93
SiO_2	17.53	77.90	27.61	52.07
P_2O_5	0.00	0.00	0.00	0.57
SO_3	4.73	5.66	3.37	2.26
K_2O	1.96	7.78	0.50	0.99
CaO	68.57	2.00	45.56	7.17
TiO_2	0.00	0.00	0.43	0.00
Fe_2O_3*	2.60	1.98	0.63	3.81
Others	0.00	0.70	0.00	1.84
$SiO_2 + Al_2O_3 + Fe_2O_3$		80.41	40.62	85.81
$CaO+(SiO_2 + Al_2O_3 + Fe_2O_3)$	91.88	82.41	86.17	92.97
Total	100.00	100.00	100.00	100.00

*Fe_2O_3 as shown here represents total Iron Oxides (Fe_2O_3; Fe_3O_4 and FeO) composition as the variant of these oxides of Iron cannot be separated in such analyses as a SEM. Hence the "sameness" specification for mill scale as provided in the literature [35] is adopted.

Table 4
Trend Line ($A + B\log\frac{t_d}{t_1}$) for Early-Age Strength of HPCs with SAP.

Binary Cement - HPCs							
Specimen	A	B	R^2	Specimen	A	B	R^2
M_2	41.39	36.19	0.863	M_3	36.37	37.623	0.947
M_2SP_1-0.2	30.20	36.24	0.987	M_3SP_1-0.2	31.87	27.402	0.917
M_2SP_1-0.3	13.55	36.28	0.980	M_3SP_1-0.3	18.07	32.251	0.968
M_2SP_1-0.4	17.96	25.23	0.946	M_3SP_1-0.4	17.89	24.112	0.931
M_2SP_2-0.2	27.70	30.41	0.977	M_3SP_2-0.2			
M_2SP_2-0.3	34.20	22.33	0.885	M_3SP_2-0.3			
M_2SP_2-0.4	28.30	22.32	0.952	M_3SP_2-0.4			
Ternary Cement - HPCs							
M_{1F}	39.01	31.184	0.999	M_{1S}	45.34	36.459	0.996
$M_{1F}SP_1$-0.2	21.68	33.986	0.994	$M_{1S}SP_1$-0.2	30.90	30.811	0.954
$M_{1F}SP_1$-0.2	19.25	32.418	0.993	$M_{1S}SP_1$-0.3	21.54	35.732	0.989
$M_{1F}SP_1$-0.2	16.96	26.276	0.991	$M_{1S}SP_1$-0.4	18.37	29.613	0.953
$M_{1F}SP_2$-0.2				$M_{1S}SP_2$-0.2	22.30	31.043	0.967
$M_{1F}SP_2$-0.3				$M_{1S}SP_2$-0.3	15.01	33.109	0.970
$M_{1F}SP_2$-0.4				$M_{1S}SP_2$-0.4	5.28	37.736	0.930

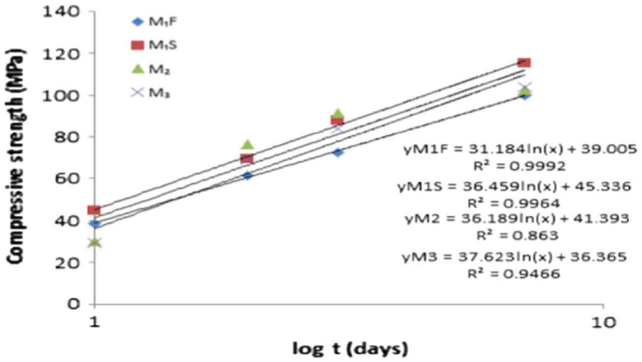

Fig. 2. Early-age strength development of reference mixtures.

ing Al_2O_3 and Fe_2O_3 (alkaline) content contribution from FA and CS) as pointed out in the work of Kakade [37]. The SAP absorption capacity at 10 mins for both SP_1 and SP_2 for the W/C (3.7, 3.1 and 2.5) to which the HPC mixtures falls (i.e. 0.3, 0.25 and 0.2 W/B pore solution) as presented in Table A-1 of Appendix averaged as 25 g/g adopted for this study. This is in agreement with the 10–30 g/g CPS of SAP as specified by [19] for SAP as IC-agent in concrete.

The early-age strength development plot for the reference mixes (Fig. 2) shows conformance with the relationship postulated by [38] for SF–concrete between one to ten days (t_1–t_{10}) of hydration.

The compressive strength increased linearly according to the logarithm of time t (Eqn. 2)

$$R = A + B\log\frac{t_d}{t_1} \tag{2}$$

where the coefficient A is the intercept on the compressive strength axis,

B is the kinetics of the hydration reaction

t_d is the age at time of testing (in days)

t_1 is demoulding time = the day one after (i.e. 24 hrs) casting

Table 4 shows the summary of trend lines. The M_3 and M_{1F} mixtures were studied with SAP size 1 (SP_1) while M_2 and M_{1S} mixtures had both SAP sizes (SP_1 and SP_2).

The coefficient, B, in this particular test, increased slightly as the W/B increased. Further influence of the additional pozzolanic materials (FA and CS) in the ternary cements mixtures was evident on the kinetics of the hydration reaction with reference to SF content being constant (7.5%) for all mixtures. The results show a higher value of B for the mixtures made from ternary cements having CS added (M_{1S}) than one in which FA was added (Table 4). This implies that the addition of CS enhanced early–age strength development more than FA. The CS reference mixture (M_{1S}) exhibited the highest 7-day compressive strength of 115 MPa from the initial one–day strength of 44 MPa. The FA mixture (M_{1F}) on the other hand, had a 7-day compressive strength of 100 MPa from one–day strength of 39 MPa. The binary cement mixtures (M_2 and M_3), however, present similar values of B. The 1 and 7 days compressive strength values of M_2 can be considered non-conforming, hence the slight drop in the R^2 value of the regression equation.

The results show that compressive strength at an early–age decreases as the SAP content increases for all HPC mixtures. The compressive strength increases linearly according to the logarithm of time t for all the HPCs containing SAP as IC-agent, also conforming to the Kadri *et al.* [38] expression of Equation (2). All the HPC mixtures (Table 4) show similar values for coefficient B (kinetics of hydration reaction) at a good correlation (R^2) for all levels of SAP addition.

3.3. Long-term strength development

Tables 5 and 6 present the density of binary and ternary cement HPCs, respectively, as influenced by SAP addition. The SAP porosity factor was calculated in comparison with the average demoulded density of twelve specimens of the respective reference mixtures as earlier explained in Section 2.2.2.

The general trend shows a slight decrease in the density of the HPCs as the SAP content increases. This indicates that the addition of SAP leads to an increase in porosity of HPC. The observed increase in porosity in the HPC specimens is in agreement with the expectations for SAP-modified concrete [3].

Results of compressive strength development over the hydration periods (7, 28, 56 and 90 days) studied for the various HPC mixtures with SAP (SP_1 and SP_2) are shown in Figs. 3 to 6.

The results show that the compressive strength increased as the hydration age increases at a decreasing rate for all the HPC mixtures. The strength, however, decreases as the SAP content increases for both SAP sizes.

The strength factor revealed that for the binary cement HPCs (M_2 and M_3), similar values as the 28–day strength of the reference mixtures were attained for HPC containing SAP at the 90-day of curing up to 0.3% b_{wob} SAP addition for both SAP sizes. The ternary cements – HPCs (M_{1F} and M_{1S}) also attained similar and above the 28-day strength values for all mixtures and SAP contents studied at the 90-day. M_3SP_1-0.3 (90–day), M_3SP_2-0.3 (56 and 90–day) and $M_{1F}SP_1$-0.2 (7–day) are noted to be inconsistent with the observed trend.

The coefficient of variation (CoV) of the compressive strength values was found to be below (8.67%) with one of the non-conforming values (M_3SP_2–0.3) having the highest (8.67%) CoV value. The trend of the results of the long-term compressive strength of the HPC with SAP agrees well with the findings of previous researchers [15,39,40] for SAP application and extra water provided for SAP absorption. It can, therefore, be inferred from the result above that 0.3% b_{wob} SAP addition is the optimum for effective internal curing in HPC.

3.4. Discussion of results

The results (Tables 5 and 6) reveal that the density of the HPC, like the compressive strength, is influenced by the SAP contents. The density, though relatively stable over the curing ages, decreased slightly as the SAP contents increased. This is an indication that SAP addition contributed to the air content in the HPC. Densities for all the HPCs containing SAP studied were observed to be within the weight classification of normal weight concrete [40]. The density shown in Fig. 7 is within the 2300 to 2500 kg/m^3 range – normal weight classification reflecting a negative correlation between the density and SAP contents of the HPCs.

Statistical analysis using a general linear model – univariate analysis for each dependent variable (Table A-5, Appendix) revealed three individual variables (W/B, SAP contents and binder type) as having a significant effect on the density of the HPCs. Two variables (SAP size and curing age) on the other hand, were found not to be of significant effect.

The combined effect of W/B with the other three variables (SAP content, SAP size and curing age) as two-factor analysis was insignificant on density, so also is the combined effect of binder type and curing age (Table A-5, Appendix – light blue highlight). The least significant in this instance is W/B combined with curing age. Three and four variable combination effects on density were mostly insignificant (Table A–5, Appendix - green highlights) with only two cases as an exception. The variables having the most significant influence on the density of the HPC mixtures studied are the SAP content and binder type. The individual effect of these two variables and the combined effects with other variables are observed to be of significant influence on the density of the HPC mixtures.

The general linear model – univariate analysis (Table A-6, Appendix) shows each dependent variable to be of significant effect on the compressive strength at both the single and two-variable interaction levels. The three-factor analysis, however, reveals two combination situations (W/B * SAP size * Curing Age and SAP size * Binder type * Curing Age) to be of no significant effect on compressive strength while all other three-factor combi-

Table 5
Density of binary cement HPC with SAP.

Curing Age	Density (kg/m^3)				SAP Porosity factor (%)*			
	7 days	28 days	56 days	90 days	7 days	28 days	56 days	90 days
M_2	2504	2495	2494	2494	100.7	100.4	100.3	100.3
M_2SP_1-0.2	2472	2461	2468	2473	99.4	99.0	99.3	99.5
M_2 SP_1-0.3	2431	2436	2441	2460	97.8	98.0	98.2	99.0
M_2SP_1-0.4	2413	2404	2422	2418	97.1	96.7	97.4	97.3
M_2SP_2-0.2	2477	2478	2488	2475	99.6	99.7	100.1	99.6
M_2SP_2-0.3	2431	2428	2434	2428	97.8	97.7	97.9	97.7
M_2SP_2-0.4	2424	2429	2417	2425	97.5	97.7	97.2	97.6
M_3	2432	2431	2434	2423	100.8	100.7	100.9	100.4
M_3SP_1-0.2	2406	2416	2414	2421	99.7	100.2	100.0	100.4
M_3SP_1-0.3	2358	2341	2362	2372	97.8	97.0	97.9	98.3
M_3SP_1-0.4	2366	2366	2381	2377	98.1	98.1	98.7	98.5
M_3SP_2-0.2	2402	2412	2386	2398	99.6	100.0	98.9	99.4
M_3SP_2-0.3	2409	2408	2393	2409	99.9	99.8	99.2	99.9
M_3SP_2-0.4	2357	2360	2326	2340	97.7	97.8	96.4	97.0

*SAP porosity factor is calculated as a percentage in relation to the average of demoulded density of the twelve specimens of reference HPC mixtures. SAP porosity is, therefore, 100- SAP porosity factor.

Table 6
Density of ternary cement HPC with SAP.

Curing Age	Density (kg/m^3)				SAP Porosity factor (%)*			
	7 days	28 days	56 days	90 days	7 days	28 days	56 days	90 days
M_{1S}	2486	2510	2503	2521	99.5	100.5	100.2	100.9
$M_{1S}SP_1$-0.2	2440	2449	2440	2453	97.7	98.0	97.7	98.2
$M_{1S}SP_1$-0.3	2437	2458	2473	2435	97.6	98.4	99.0	97.5
$M_{1S}SP_1$-0.4	2420	2432	2448	2451	96.9	97.4	98.0	98.1
$M_{1S}SP_2$-0.2	2471	2468	2397	2426	98.9	98.8	96.0	97.1
$M_{1S}SP_2$-0.3	2486	2438	2448	2445	99.5	97.6	98.0	97.9
$M_{1S}SP_2$-0.4	2436	2437	2416	2413	97.5	97.6	96.7	96.6
M_{1F}	2494	2487	2488	2498	100.7	100.4	100.5	100.9
$M_{1F}SP_1$-0.2	2422	2440	2422	2445	97.8	98.5	97.8	98.7
$M_{1F}SP_1$-0.3	2394	2397	2395	2389	96.7	96.8	96.7	96.5
$M_{1F}SP_1$-0.4	2405	2412	2401	2402	97.1	97.4	97.0	97.0
$M_{1F}SP_2$-0.2	2456	2439	2419	2435	99.2	98.5	97.7	98.3
$M_{1F}SP_2$-0.3	2406	2406	2410	2412	97.2	97.2	97.3	97.4
$M_{1F}SP_2$-0.4	2407	2420	2416	2414	97.2	97.7	97.5	97.5

*SAP porosity factor is calculated as a percentage in relation to the average of demoulded density of the twelve specimens of reference HPC mixtures. SAP porosity is, therefore, 100- SAP porosity factor.

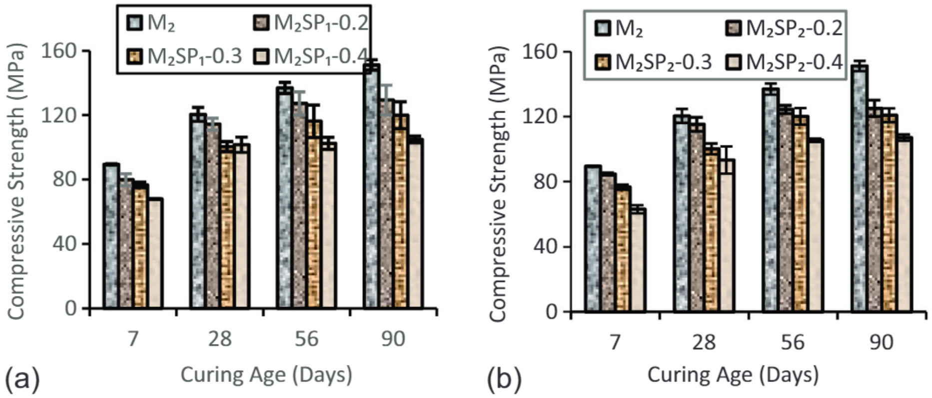

Fig. 3. Compressive strength of M2 (a) with SP1 and (b) with SP2.

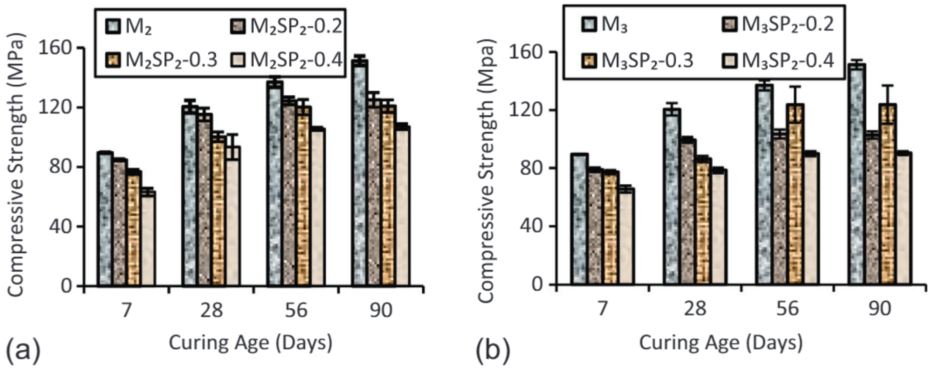

Fig. 4. Compressive strength of M3 (a) with SP1 and (b) with SP2.

nation types are significant. The four-factor analysis further shows that binder type in combination with SAP size, SAP content and curing age had a significant effect on the compressive strength. However, the W/B combination with the same set of factors (i.e. purple highlight on Table A-6, Appendix) is of no significant influence on the compressive strength. This implies that the binder type is of more importance in the outcome of the compressive strength than the W/B within limits (0.2–0.3 W/B) examined in the study and the three binder types tested. Although all the independent variables (W/B, SAP size, SAP contents, binder type and curing age) as single and two-variable combinations have a significant effect on the compressive strength. The binder type has greater impact when the combined effects are considered.

The influence of binder type on strength is noted to be related to the W/B since HPCs made with Binder Type 1 (M_2 and M_3) comprise of two W/B (0.25 and 0.3), respectively, as presented in Fig. 8. Fig. 9 reveals that ternary cements (Binder Types 2 (M_{1F}) and 3 (M_{1S})) had higher strength values than the binary cements at ages beyond 7–day. Binder Type 2 (CEM I 52.5 N + SF + FA) – HPC reports better long-term (90–day) strength development trend than Binder type 3 (CEM I 52.5 N + SF + CS). The higher SiO_2 content in FA continues to react with excess lime (CaOH) lib-

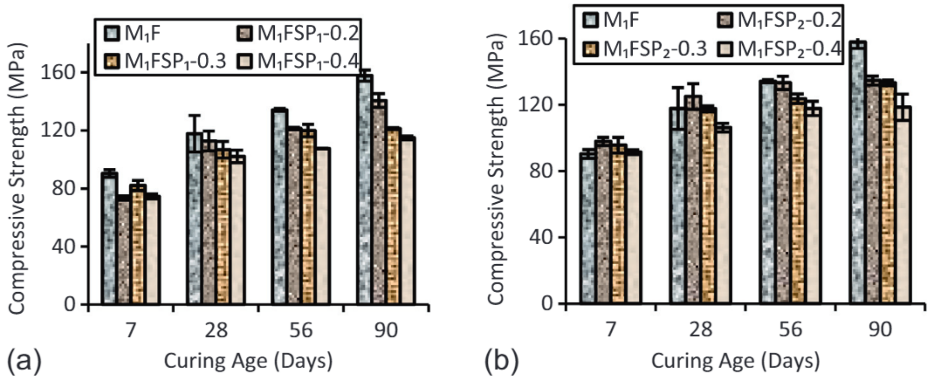

Fig. 5. Compressive strength of M1F (a) with SP1 and (b) with SP2.

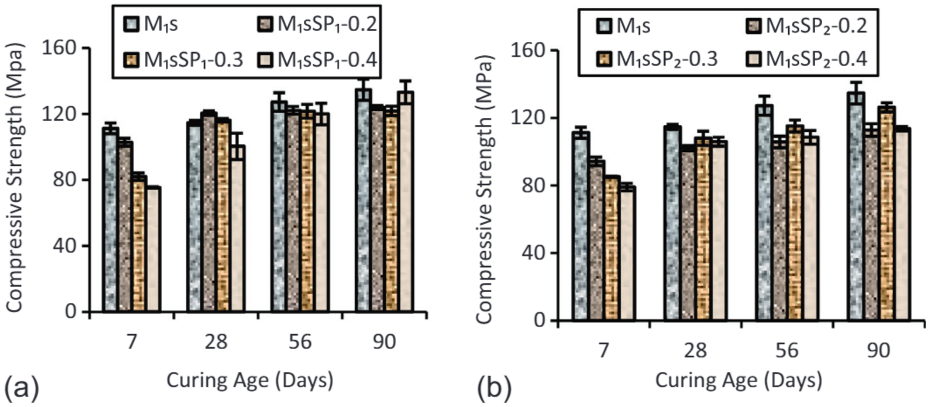

Fig. 6. Compressive strength of M1S (a) with SP1 and (b) with SP2.

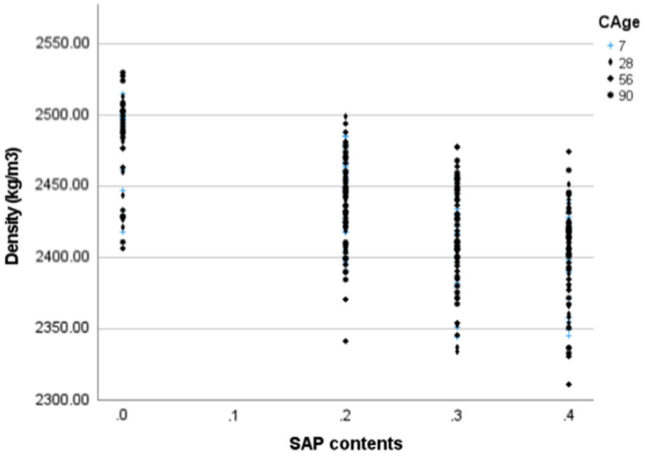

Fig. 7. Influence of SAP contents on the density of HPCs.

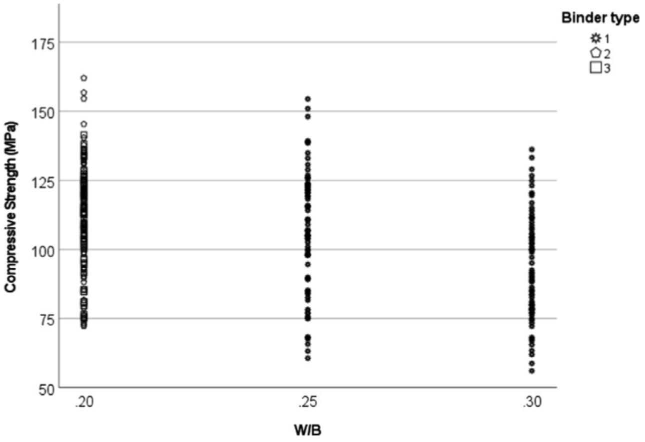

Fig. 8. Compressive strength versus binder type as influenced by W/B.

erated by CEM I 52.5 N and resulted in better long-term strength than the CS–based ternary cement HPC with high CaO content. Since all the HPCs have the same proportion of SF (7.5% b_{wob}), the lower compressive strength results from the HPCs with the highest W/B (M_3 - HPC) within the same binder type (Type 1 for M_2 and M_3) agree with expectation since higher water content for the same binder content leads to lower strength in concrete.

The influence of SAP content on the long-term strength is further illustrated in Fig. 10, which shows that the mean compressive strength generally decreases as the SAP content increases.

The mean compressive strength was observed to be above 100 MPa for SAP addition up to 0.3% $b_{wob.}$ This implies that despite the slight strength decrease as a result of SAP addition, all the HPCs with or without SAP gave long-term strength surpassing the minimum 28-day target strength of 70 MPa .

Fig. 11 presents the long-term strength development of the reference mixtures on a logarithmic time scale. Further, Table 7 presents a summary of the equations of trend lines obtained from the plots for long-term strength development.

The long-term strength was observed to also conform to Equation (2), as proposed by [38]. It increased linearly according to the

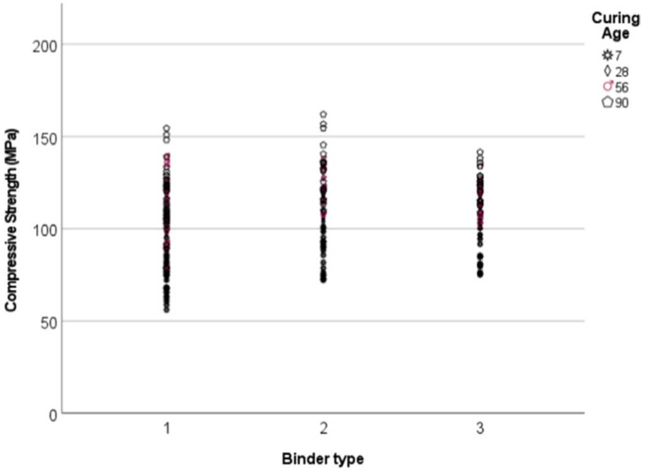

Fig. 9. Compressive strength versus binder type as influenced by curing age.

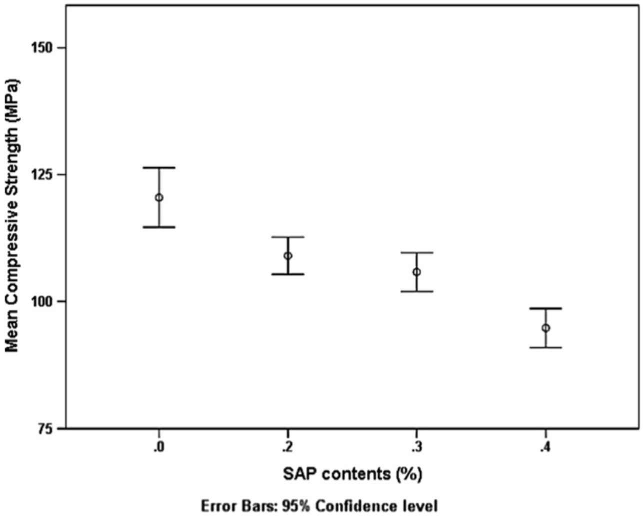

Fig. 10. Mean compressive strength against SAP contents.

logarithm of time for all the HPCs studied at a good correlation for all levels of SAP addition. An increase in W/B in the binary cement – (M_2 and M_3) mixtures led generally to a decrease in the B coefficients (Table 7), so does the increase in SAP contents except in a few cases. The coefficient B in ternary cement HPCs containing FA (M_{1F} series) also decreased generally as the SAP content increases, while the M_{1S} series (containing CS) reflect a different pattern. The M_{1S} series which show a high value of the B coefficient for the early-age strength was, however, observed to display lower values of B coefficient for the long-term strength development especially at low (0 and 0.2%) SAP content. SAP addition can, therefore, be adjudged to be more advantageous and resulted in better long-term strength development for the FA mixtures.

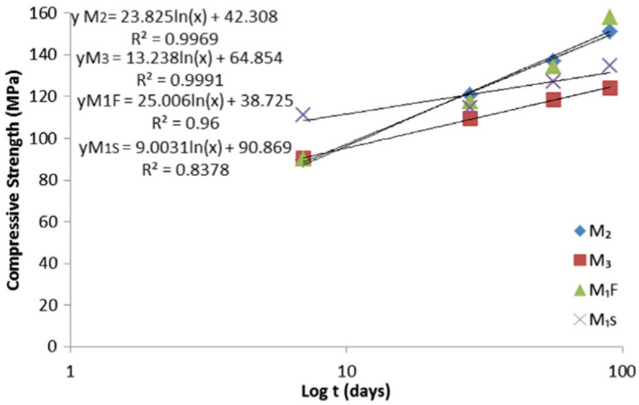

Fig. 11. Compressive strength of reference mixtures on a log time scale.

3.5. Curve-fitting and modelling

The curve fitting and modelling in this study were based on the concepts highlighted by [16] as follows:

i. Concrete compressive strength is proportional to the compressive strength of the paste phase.
ii. Paste compressive strength depends on the gel space ratio, as suggested by [41].
iii. The influence of air voids created by SAP on compressive strength can be accounted for by Bolomey's formula (Equation (3)) provision for air content in concrete [15].

The air contents (excluding SAP voids) using direct weight measure of demoulded concrete vary from 0.0 to 3.87% as influenced by the varied HPC mixture contents. The measured early-age and long–term compressive strength values were corrected accordingly for the air content to study the effect of SAP using Eq. (3).

$$f_c = K_{Bolomey}((1/W/C) - 0.5) \times (1 - B \times (a - a_0)) \tag{3}$$

$K_{Bolomey}$ remains constant and of the same value for all mixtures (since all the HPCs are made from the same aggregate), a is the actual air content (% relative to the volume of concrete), and a_0 is a reference air content. The value of constant B of Equation (3), according to Hasholt et al. [16], as a rule of thumb equals 0.04, when the paste phase occupies 25% of the concrete volume. The reference HPCs have paste contents (volume of binder + water) as 29% (M_{1F} and M_{1S}); 31% (M_2) and 32% (M_3), respectively. The constant B for the compressive strength in line with Equation (3) was thereby determined, as shown in Table 8.

The compressive strength of the mortar cubes (corrected for air and SAP voids) with age is shown in Fig. 12 (for HPC containing SP_2) and Fig. 13 (for HPC containing SP_1).

The 28-day strength of mortar cubes was not available from test results because the test on strength development and degree of hydration as explained in Section 2.2.1 were limited to 7 days. This was due to difficulty of milling the mortar cubes manually adopting the ACV mould. The 28-day strength for the mortar cubes used for the plot was thereby calculated by interpolation using the values obtained from the long-term strength tests conducted on the HPC mixtures with coarse aggregates.

Plots of compressive strength of the mortar cubes (corrected for air and SAP voids) with age shown in Fig. 12 (for HPC containing SP_2) and Fig. 13 (for HPC containing SP_1) gave a good trend.

It reflects that some differences exist in the compressive strength of the mortar cubes when corrected for air and SAP voids using the Bolomey's formula. The strength development trend up to 28 days fits well into a logarithmic curve with the trendline cutting across the 0.2% and 0.3% SAP contents (b_{wob}) in most instances. This further affirms the 0.3% SAP contents (b_{wob}) as optimum SAP addition for the SAP type and sizes used in this study.

The gel space ratio for respective mixtures (M_{1F}, M_{1S}, M_2 and M_3) were calculated and plotted against the compressive strength of the various mortar cubes as presented in Fig. 14.

Neville [22] defined the gel space ratio as the ratio of the volumes of the hydrated cement to the sum of the volumes of the

Table 7
Trend line for compressive strength of HPCs with SAP.

Binary cement							
Specimen	A	B	R^2	Specimen	A	B	R^2
M_2	42.31	23.825	0.997	M_3	64.85	13.238	0.999
M_2SP_1-0.2	42.93	20.221	0.968	M_3SP_1-0.2	54.33	11.808	0.991
M_2SP_1-0.3	42.62	17.599	0.990	M_3SP_1-0.3	33.58	16.919	0.954
M_2SP_1-0.4	43.59	14.686	0.805	M_3SP_1-0.4	46.03	7.990	0.838
M_2SP_2-0.2	55.08	16.604	0.945	M_3SP_2-0.2	61.98	9.899	0.898
M_2SP_2-0.3	40.77	18.452	0.970	M_3SP_2-0.3	33.63	20.018	0.829
M_2SP_2-0.4	30.35	17.990	0.965	M_3SP_2-0.4	45.49	10.332	0.968
Ternary Cement							
M_{1F}	37.33	25.006	0.960	M_{1S}	90.87	9.003	0.837
M_{1F} SP_1-0.2	25.39	25.113	0.981	$M_{1S}SP_1$-0.2	88.31	8.411	0.911
M_{1F} SP_1-0.3	61.60	12.288	0.743	$M_{1S}SP_1$-0.3	54.17	16.294	0.899
M_{1F} SP_1-0.4	45.80	15.630	0.975	$M_{1S}SP_1$-0.4	29.82	22.425	0.986
M_{1F} SP_2-0.2	70.92	15.003	0.954	$M_{1S}SP_2$-0.2	80.33	6.787	0.952
M_{1F} SP_2-0.3	68.19	14.291	0.989	$M_{1S}SP_2$-0.3	50.01	15.537	0.990
M_{1F} $SP_2$0.4	69.63	11.249	0.975	$M_{1S}SP_2$-0.4	55.27	13.469	0.937

Table 8
Correction factor for Reference HPCs.

HPC type		Paste content	constant*B*
Ternary cements - HPCs	M_{1F} and M_{1S}	0.29	0.034
Binary cements - HPCs	M_2	0.31	0.032
	M_3	0.32	0.031

hydrated cement and the capillary pores. Hence, the expression for this study is given as presented in Eq. (4):

$$X = \frac{2.06 v_c \propto_c}{v_c \propto_c + \frac{w}{c}} \tag{4}$$

where X is the gel space ratio of the HPC mortar paste; v_c is the specific volume of anhydrous binder (i.e. binary or ternary); $\propto_c$is the degree of hydration of binder and W/C is the original water to binder ratio [22].

The plot in Fig. 14 reveals for these low W/B mixtures as follows:

i. the compressive strength of mortars cubes (with or without SAP addition) against the gel space ratio has a trend similar to that propounded by the Powers' Model
ii. Using Bolomey's formula in the Powers' Model accounts for the influence of air and SAP voids on the compressive strength up to the 7th day to which this study was able to determine the degree of hydration.
iii. The relationship deduced from the results in Fig. 14 can be expressed as shown in Eq. (5):

$$f_c = 201X^{2.86} \tag{5}$$

This is similar to the expression adopted in the works of Hasholt *et al.* [16] from the modified relation presented by (Powers, 1958) shown as Eq. (6).

$$f_{c=AX^3, X=\frac{volumeofgel}{volumeofspace}} \tag{6}$$

The trendline power value of 2.86 is very close to 3 as proposed in the Powers' Model while the constant A is 201. It is however noted that the R^2 is 0.74 because of the many variables (binder types, W/B, curing age, SAP size and content) combined in the plots. Hasholt *et al.* [16] reported a similar result of 2.88 power value and 299 as constant at an R^2 of 0.97. The power value in Equation (6), according to the literature [22,27] is expected to be approximately three while the value arrived at for the constant A could vary as influenced by the binder type.

The results from this study reveal that SAP addition leads to a slight reduction in the compressive strength of the low W/B HPC, while correction made for void volume (SAP and air) using the Bolomey's formula and Powers gel-space ratio enhanced a good fit into the Powers' Model. This makes it possible to predict the SAP effect on the compressive strength of HPC.

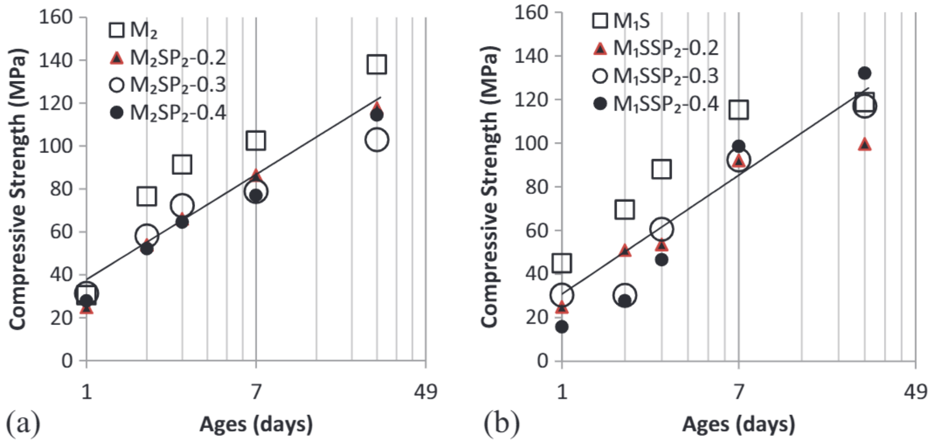

Fig. 12. Compressive strength of mortars cubes corrected for both air and SP2 voids (a) M2; (b) M1S.

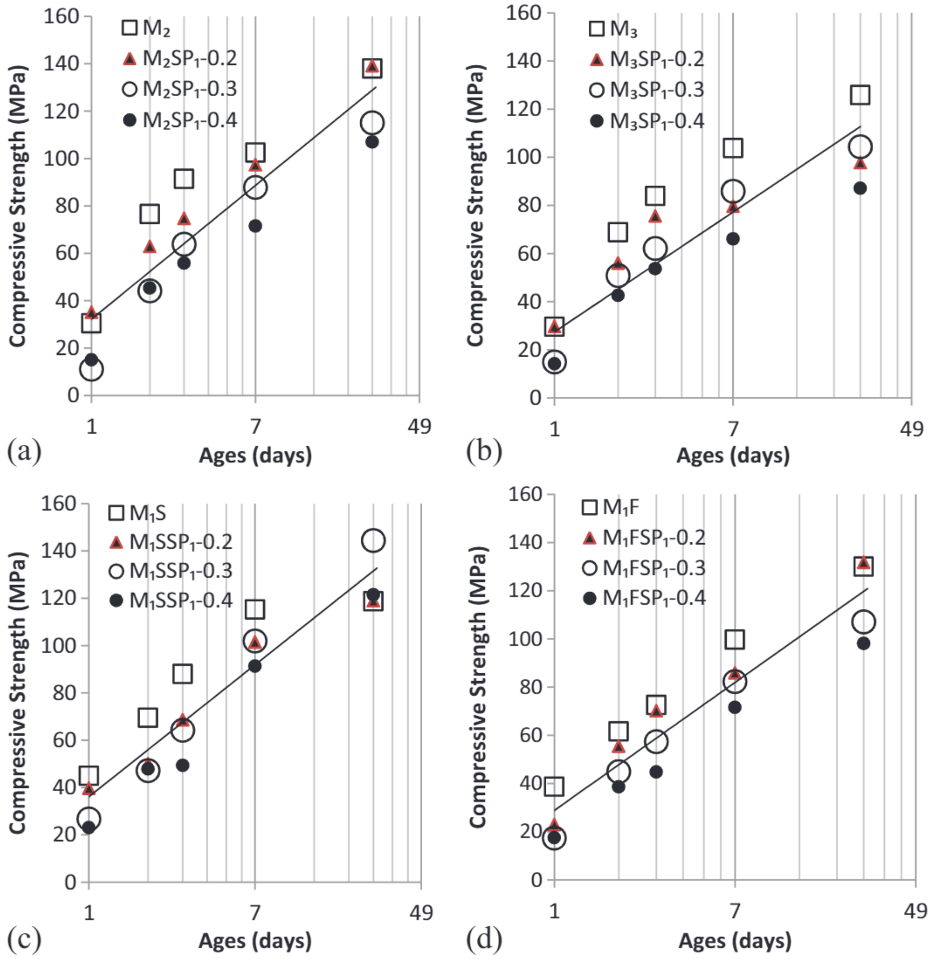

Fig. 13. Compressive strength of mortar cubes corrected for both air and SP1 voids (a) M2; (b) M3; (c) M1S and (d) M1F.

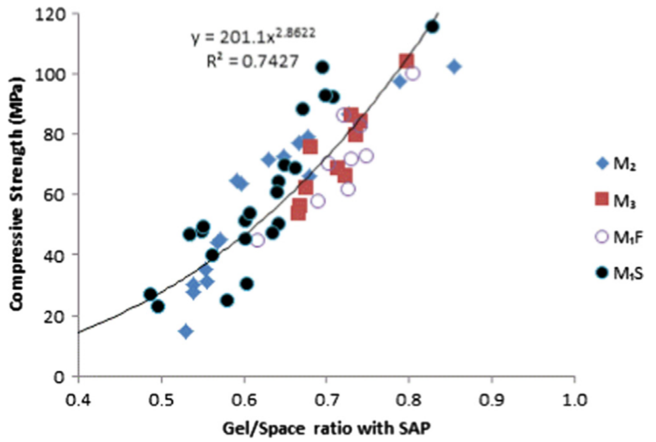

Fig. 14. Compressive strength against the gel/space ratio for HPC mortar cubes.

4. Conclusion and recommendations

The outcome of this study on early-age and long-term strength development of HPC containing SAP as IC-agent can be summarised as follows:

i. SAP addition to HPCs contribute to the air content in the concrete as the density of the HPCs decreased at a relatively low rate as the SAP content in the concrete increases.
ii. The compressive strength of the HPC mixtures decreased slightly (both for the early-age and long-term) as SAP contents increases.
iii. Strength development of the HPCs with SAP (at both the early-age and long-term) increased linearly according to the logarithm of time for all the HPCs studied at a good correlation for all levels of SAP addition.
iv. All the independent variables (W/B, SAP size, SAP contents, binder type and curing age) are of significant effect on the compressive strength as single and two-variable combinations. Binder type's effect is, however, the most significant when the combined effects were considered.
v. The supposed influence of binder type on strength was noted to be related to the W/B incorporated since HPCs made with Binder Type 1 (M_2 and M_3) comprise of two W/B (0.25 and 0.3). Hence the total W/B is a major determinant on the strength development in the HPCs with or without SAP.
vi. 0.3% SAP contents (b_{wob}) is the optimum for effective IC provision in low W/B HPCs when adopting the SAP type used in this study.
vii. A combination of void volume correction by the Bolomey's formula and the Powers gel–space ratio is a useful model for predicting the effect of SAP addition on the compressive strength of the low W/B HPCs.

In conclusion, this study offers that SAP addition leads to a slight reduction in compressive strength of HPC while correction made for void volume (SAP and air) using the Bolomey's formula and Powers' gel-space ratio enhanced a good fit into the Powers' Model. This makes for possible prediction of the SAP effect on the compressive strength of the low W/B HPC. SAP incorporation to a limit of 0.3% b_{wob} with moderate additional water for SAP absorption is recommended in low W/B HPC based on the outcome of this study.

CRediT authorship contribution statement

Babatunde J. Olawuyi: Methodology, Investigation, Formal analysis, Data curation, Writing - original draft. **Adewumi J. Babafemi:** Formal analysis, Writing - review & editing. **William P. Boshoff:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.conbuildmat.2020.121798.

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