Comparative Study of Superabsorbent Polymers and Pre-soaked Pumice as Internal Curing Agents in Rice Husk Ash Based High-Performance Concrete

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Abstract. Utilisation of superabsorbent polymers (SAP) and pre-soaked lightweight aggregates (LWA) as internal curing (IC) agents for the mitigation of autogenous shrinkage and micro-cracking of high strength/high-performance concrete (HSC/HPC) have been well researched and documented in literature. Rice husk ash (RHA) on the other hand has been adjudged to be of good pozzolanic activity and a possible alternative to silica fume (SF) in low water/binder (W/B) concrete production. An experimental comparative study was conducted in the current work to assess the effectiveness of the two known IC-agents on rice husk ash (RHA) based HPC. HPC mixtures of $f_{c,cube28} = 60$ MPa minimum target strength produced and internally cured with 0.3% content of SAP by weight of binder (b_{wob}) and varied content of pre-soaked pumice (5 to 10% in steps of 2.5%) by weight of coarse aggregate (b_{wocg}) were cast using 100 mm cubes samples. Thereafter, the samples were cured for 7, 14, 28 and 56 days by water immersion before subjecting them to compressive strength test. The results showed 0.2% b_{wob} SAP HPC ($SHPC_1$) to be the best performed internally cured HPC at the early ages with similar long-term strength values as 5 and 7.5% b_{wocg} saturated pumiced HPC ($PHPC_{1\&2}$). The study thereby recommends SAP content of 0.2% b_{wob} and saturated pumice content up to 7.5% b_{wocg} for use as IC-agent in HPC.

Keywords: Superabsorbent polymers (SAP) · Pre-soaked lightweight aggregates (LWA) · Rice husk ash (RHA) · Compressive strength · High-performance concrete (HPC)

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1 Introduction

High-performance concrete (HPC) utilisation in building construction is getting popular in the recent years due to the unique properties of low water/binder (W/B), high strength, high modulus of elasticity and possibility of having relatively thin sections for construction of tunnels, precast pylons, bridges, shotcrete repairs, tall buildings, parking garages and more (Aïtcin 2004; Orosz 2017). HPC is defined by American Concrete Institute, ACI (1999) "as concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using traditional constituents and normal mixing, placing, and curing practice". Production of this low W/B concrete is known to often require incorporating other cementitious material especially silica fume (SF) – a scarce and expensive commodity in sub-Saharan Africa especially Nigeria. The non-availability of SF therefore necessitates consideration for rice husk ash (RHA) which has been adjudged to be of good pozzolanic activity and possible alternative to silica fume.

RHA is an agro-industrial waste obtained through calcination of rice husk in a controlled environment. De Sensale and Viacava (2018) estimated RHA generation around the globe to about 20 million tonnes where the husk accounts for about 20% by weight of rice paddy and after burning the husk, ash obtained is in the range of 20–25% of the total weight of the husk (Kaur et al. 2018). RHA is known to be of low density and very high silica content when calcined in controlled setting. Its specific gravity ranges from 2.05–2.53 which is lower than the 3.5 value of PC (Fapohunda et al. 2017). The work of Fapohunda et al. (2017) reported the cumulative useful oxide (SiO_2+Al_2O_3+Fe_2O_3) of RHA calcined in a controlled incinerator to be above 70% conforming to Class F fly ash of ASTM C618 (2015). Limitation of RHA in Nigeria at reaching the optimum pozzolanic reactivity in concrete products was also noted and this was attributed to poor calcination methods in an uncontrolled incineration facility. Largely, the burning temperature in a suitable incinerator is an important factor that affect the amorphous state of RHA in concrete and mortar applications.

HPC however comes with attendant autogenous shrinkage and micro-cracking mitigation for which superabsorbent polymers (SAP) and pre-soaked lightweight aggregates (LWA) used as internal curing is found as possible solution, well researched and documented. Previous studies (Persson 1997; Kovler and Jensen 2005; Bentz and Weiss 2011; Di Bella et al. 2012, 2016) have empirically revealed that HPC is essentially a concrete with low W/B ranging from 0.2–0.38. The substantial amount of cement and supplementary cementitious materials (SCMs) inherent in the mix results in increased temperature upon water addition and densification within the concrete area. Savva et al. (2018) inferred a direct relationship between ambient temperature and pozzolanic activity of cementitious materials. The authors posit that cementitious grains are usually influenced by ambient temperature; hence a fast reaction which hinders uniform distribution of hydration products leading to an increase in porosity of hydrated gel. In the same vein, inclusion of SCM furthers the propagation of autogenous shrinkage, chemical shrinkage and self-desiccation due to combined effects of hydration and pozzolanic reaction necessitating higher moisture demand in the concrete (Wu et al. 2017). Nduka et al. (2018) also observed issues of concern such as like difficulty in curing vertical members, inaccessible locations in buildings and poor workmanship when external curing methods are used in HPC structures. Consequently, to mitigate these challenges in concrete production, an innovative curing technique termed "internal curing (IC)" has gained tremendous attention in literature and practice in producing HPC.

Traditionally, two types of curing systems (internal and external) exists in maintaining the internal temperature and relative humidity of all sections of concrete types. Internal curing (IC) is achieved by incorporating materials that have the capacity to absorb and desorb water during the plastic and hardened state of designed concrete respectively (Tu et al. 2019). The dispersed materials provide additional water internally to the cementitious materials thereby furthering hydration process and subsequently reduced self-desiccation otherwise known as autogenous shrinkage. Two notable materials (Light weight aggregates and SAP) have been used in past studies and practice in advancing internal curing techniques. Studies examining the effectiveness of the two IC-agents on RHA based HPC mix subjected to same curing regimes is scarce in literature. The current study is thereby an attempt to fill this gap on performance assessment of both SAP and pre-soaked pumice as IC-agent in RHA based HPC.

2 Experimental Procedure

2.1 Materials

The materials used for the study are SAP, pumice stone, crushed granite stone, natural sand, cement (CEM II 42.5 N), rice husk ash (RHA), water and superplasticizer. The SAP is a thermoset polymer specifically the covalently cross-linked polymers of acrylic acid and acrylamide, neutralised by alkali hydroxide produced by SNF Floerger in France. The SAP "FLOSET 27CC" of grain size $\geq$ 600 µm as described in Olawuyi and Boshoff (2017) was incorporated at 0.2% and 0.3% contents (by weight of binder – b_{wob}) as IC-agent as a comparative study to saturated pre-soaked pumice (13 mm maximum grain size) at varied contents (5%, 7.5% and 10%) of coarse aggregate. SAP absorption capacity of 12.5 g/g as recommended in Olawuyi (2016) was adopted for additional water provision in this study.

CEM II/A-LL, 42.5 N (3X) from Dangote Cement, Obajana Plant conforming to BS EN 197-1 (2011) and NIS 444-1 (2003) was used as the main binder (PC) and RHA obtained from Rice husk acquired from rice mill in Minna, Niger State, Nigeria served as the SCM for this study. The rice husk was calcined to ash at 700 °C in a controlled incinerator and pulverised using a grinding mill at Building Laboratory, Federal University of Technology (FUT), Minna. The RHA powder was white in colour - an indication of complete burning of all carbon and impurities within the husk. The powdered PC and RHA were then packaged and sent to Ewekoro factory of Lafarge Cement for X-ray florescence (XRF) analysis to determine their oxide composition. Blends of the binders (as presented in Table 1 shows the two reference HPC mixtures).

The natural sand used at air dry condition 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 (Aïtcin 1998; Beushausen and Dehn 2009; Neville 2012). The sand has the following physical characteristics: Fineness Modulus – FM = 2.87, Coefficient of uniformity – C_u = 1.23, Coefficient of curvature – C_c = 3.28 and dust content = 0.1%. This conforms to medium sand classification according to Shetty (2004). Crushed granite stone and the pumice that passed through 13 mm sieve size and retained on 9.50 mm sieve size was used as course aggregate in compliance with typical HPC mixes found in literature (Aïtcin 2004; Beushausen and Dehn 2009; Neville 2012; Olawuyi and Boshoff 2018). The crushed granite was used at saturated surface dry conditions after been washed to eliminate fine content that will likely increase water demand. The pumice was soaked in water for 24 h, removed and allowed to drain to saturated surface dry condition before use. Result of the physical properties tests on the constituent materials are found in Sect. 3.1 (Fig. 1 and Table 3).

Hydroplast-300 – a polycarboxylic ether (PCE) polymer based superplasticizer supplied by Armorsil Manufacturing Incorporation was used as the superplasticizer and administered at constant concentration of 1.5% b_{wob}.

Clean potable water studied by Ogunbayo et al. (2018) and as specified by BS EN 1008 (2002) available within the concrete laboratory of Department of Building Technology, Covenant University, Ota was used for mixing. Additional water for SAP absorption was based on 12.5 g/g of SAP (Olawuyi and Boshoff 2013) was also introduced.

2.2 Methods

2.2.1 Properties of Constituent Materials

The oxide composition of the cementitious materials (PC and RHA in powdered form) was examined at the Laboratory of the Ewekoro Factory of Lafarge Plc. About 100 g of the materials were packaged in a sealed polythene sheet and sent to the Laboratory for XRF analysis. The result is as presented in Sect. 3. The particle size distribution of the aggregate's samples (i.e. the sieved sand and granite stone) was determined by wet sieving while the specific gravity of the aggregate and binders were also determined in the Building laboratory of FUT, Minna. Section 3 further present and discuss the result of the physical properties of the constituent materials.

2.2.2 HPC Specimen Production

HPC target strength of C55/67 at 28 day with 0.3 W/B mix design utilizing British method was adopted as reference mix with the other mixes having different SAP contents (0.2% and 0.3%). The total mass of the binders in the mixes include 485 kg/m^3 (90% b_{wob}) of PC and 55 kg/m^3 (10% b_{wob}) of RHA. The details of the mix constituents for the HPC mixtures is presented in Table 1.

The different SAP contents (0.2 & 0.3b_{wob}) were included for the SAP internally cured HPCs ($SHPC_1$ and $SHPC_2$) with additional water at 12.5 g/g provided for SAP absorption while the pre-soaked saturated surface dry pumice was measured and added at required contents (5, 7.5 and 10% by weight of coarse aggregate) for the Pumice internally cured HPCs ($PHPC_1$, $PHPC_2$ and $PHPC_3$ respectively). The cast 100 mm cubes HPCs were de-moulded after 24 h and cured by full immersion for the respective ages before testing.

Table 1. Mix composition

Materials	Mixture types (kg/m^3)					
	Control	HPC with SAP		HPC with pre-soaked Pumice		
	CHPC	SHPC$_1$	SHPC$_2$	PHPC$_1$	PHPC$_2$	PHPC$_3$
CEM II 42.5 N	485	485	485	485	485	485
Rice Husk Ash-RHA (10%)	55	55	55	55	55	55
Superplasticizer (1.5% b_{wob})	8.1	8.1	8.1	8.1	8.1	8.1
Fine sand	700	700	700	700	700	700
Coarse aggregate	1050	1050	1050	997.5	971.25	945
Pre-soaked Pumice				52.5	78.75	105
SAP (0.2% & 0.3% b_{wob})		1.08	1.62			
Water	156	156	156	156	156	156
Additional water for SAP		12.5 g/g of SAP				
W/B	0.3	0.3	0.3	0.3	0.3	0.3

Legend
RHA = Rice Husk Ash
CHPC = Control HPC
SHPC = SAP internally cured HPC
PHPC = Pumice cured HPC

2.2.3 Compressive Strength and Density

HPC samples were made and cured in compliance with BS EN standards (BS EN 12350-1 & 5 2000; 12390-1 & 2 2000; 12390-3 2002) for compressive strength. The compressive strength tests were performed on 108 samples using 2000kN loading capacity ELE Compressive Strength Testing Machine at 0.5 N/mm^2 loading rate. The concrete specimens were also weighted and dimension measured immediately after de-moulding and at the respective curing ages (7, 14, 28, 56 & 90 days) after removal from curing tank for determination of the de-moulded density and final density of the hardened HPCs.

3 Results and Discussion

3.1 Physical and Chemical Properties

Result of the XRF analysis conducted on the PC and RHA powders are as presented in Table 2. The result reveal RHA is majorly SiO_2 (94%) with a silica-sesquioxide (S-S) ratio (SR) of 49.3 and aluminium sesquioxide ratio (AR) of 1.1 implying a very strong and reactive Class F Pozzolan in conformance to ASTM C618. The sum of silica, alumina and ferric oxides (SiO_2+Al_2O_3+Fe_2O_3) for the RHA (96%) is above the 70% specified for the Class of Pozzolan in ASTM C618. PC on the other hand is majorly calcium oxide (CaO - 64%). This is in agreement with oxides composition for CEM II Portland cement found in literature (Neville 2012; Mehta and Monteiro 2014).

Table 3 reveals the fine aggregate sample has coefficient of uniformity (Cu) of 2.39, coefficient of curvature (Cc) of 0.94 and fineness modulus (FM) of 2.87 implying a medium sand of Shetty (2004) classification while the granite stone and the pumice (i.e. coarse aggregates) used for the study are both a uniformly graded stones. The details of physical properties as shown in Table 3 affirms that the fine and coarse aggregates are suitable for HPC production.

Table 2. XRF result for RHA and PC

Oxides (%)	RHA	PC
SiO_2	93.6	21.5
Al_2O_3	1	5.2
Fe_2O_3	0.9	1.2
CaO	1.3	64
MgO	1.2	2.9
SO_3	0.1	4.5
Na_2O	1.7	0.6
K_2O	0.2	0.1
Minor Oxides	0	0
LOI	0	0
$SiO_2+Al_2O_3+Fe_2O_3$	95.5	27.9
SR	49.26	3.36
AR	1.11	4.33
Total	100	100

Table 3. Physical properties of materials

Item	Sand	Granite	Pumice	RHA	PC
D10	360	10000	10000		
D30	540	11000	11000		
D60	860	13000	13000		
Cu	2.39	1.30	1.30		
Cc	0.94	0.93	0.93		
FM	2.87				
SG	2.65	2.70	1.90	2.30	3.40

3.2 Compressive Strength of HPCs

Table 4 and Fig. 1 show the compressive strength of various HPCs containing equivalent quantity of CEM II 42.5 N and 10% RHA. The control HPC mixture without an IC-agent is referred to as CHPC, the mixtures with SAP incorporated are SHPCs while the HPC mixture containing varying contents of pre-soaked pumice is the PHPCs. All the HPCs show strength increases as curing age increases; the CHPC had the best early-age strength performance followed by $SHPC_1$ while the $PHPC_3$ had the lowest 7-day strength (38% below the CHPC). Comparable strength development was noticed at the 14-day of curing. $PHPC_{1\&2}$ had same strength value (48 N/mm^2) while the strength of $PHPC_3$ is 38 N/mm^2. The $SHPC_1$ strength of 55 N/mm^2 is the closest to that of the control (CHPC, 57 N/mm^2) and is 20% above that of $SHPC_2$ (47 N/mm^2) at the 14^{th} day.

Table 4. Compressive strength of HPCs and CS_{28} factor

Specimen/age (Days)	Compressive strength (N/mm^2)						$f_{cu(28)}$ factor					
	7	14	28	56	90	120	7	14	28	56	90	120
CHPC	54.00	57.00	59.83	62.67	65.33	71.00	0.90	0.95	1.00	1.05	1.09	1.19
$PHPC_1$	46.20	48.22	56.80	62.33	65.63	68.20	0.77	0.81	0.95	1.04	1.10	1.14
$PHPC_2$	45.10	48.03	56.47	62.70	68.57	71.50	0.75	0.80	0.94	1.05	1.15	1.19
$PHPC_3$	33.37	36.30	46.20	51.80	54.73	57.47	0.56	0.61	0.77	0.87	0.91	0.96
$SHPC_1$	51.33	55.00	57.92	60.00	65.42	69.58	0.86	0.92	0.97	1.00	1.09	1.16
$SHPC_2$	42.50	42.92	46.67	49.17	51.67	57.08	0.71	0.72	0.78	0.82	0.86	0.95

Legend:
CHPC – Control HPC mixture
$PHPC_1$ – 5 % Saturated Pumice HPC
$PHPC_2$ – 7.5% b_{woca} Saturated Pumice HPC
$PHPC_3$ – 10% b_{woca} Saturated Pumice HPC
$SHPC_1$ – 0.2%n b_{wob} SAP cured HPC
$SHPC_2$ – 0.3% b_{wob} SAP cured HPC
$f_{cu(28)}$ = the compressive strength value at respective curing ages as compared to the 28th day strength.

The 28-day strength for both $PHPC_1$ and $PHPC_2$ maintains similar values (56.8 N/mm^2 and 56.5 N/mm^2 respectively) while $PHPC_3$ still had the lowest strength (46.2 N/mm^2) amongst the PHPCs. $SHPC_1$ maintained a close strength value (58 N/mm^2) to the CHPC (60 N/mm^2) while $SHPC_2$ had strength of 47 N/mm^2 (22% below that of CHPC). The trend of up 28-day strength revealed $PHPC_1$&$_2$ and $SHPC_1$ had similar level of performance in strength development 95% to 97% of the control (CHPC) while $PHPC_3$ and $SHPC_2$ remains at 77 and 78% value of CHPC ($f_{cu(28)}$ Factor, Table 4).

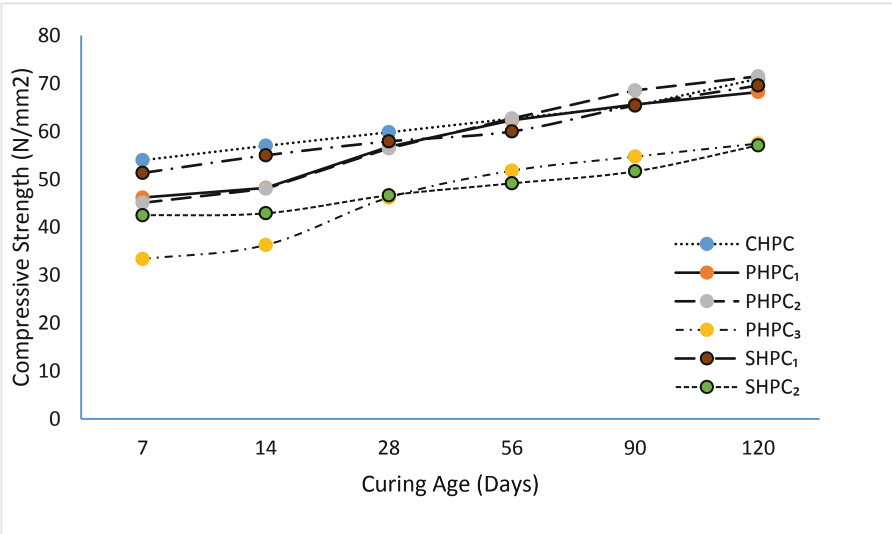

Fig. 1. Compressive strength of internally cured HPCs

Similar trend was maintained for long-term strength (56^{th} to 120^{th} day strength) with all the HPCs except $SHPC_2$ and $PHPC_3$ having values greater than the 28-day strength of CHPC at 120 days age. $PHPC_2$ (71.5 N/mm^2) met up with the control (CHPC, 71 N/mm^2) on the 120^{th} day. $SHPC_1$ is the best performed internally cured HPC at the early ages and maintained good strength values at the later ages too. The $f_{cu\ (28)}$ factor (Table 3) further showed that pumice inclusion up to 7.5% b_{wocg} has no negative influence on the strength of the RHA based HPC while the optimum SAP content for the concrete without any adverse effect is 0.2% b_{wob}.

4 Conclusion and Recommendation

The current study investigated the feasibility of actualising 60 N/mm^2 RHA based HPC using locally available light weight aggregate (pumice) and SAP as IC- agent. The HPCs were made from binary binder made of CEM II/A-LL 42.5N and 10% RHA b_{wob}. The workabilities of the HPCs was improved using Hydroplast-300 (a PCE) as superplasticizer. SAP and Pre-soaked Pumice at varying percentage replacements were added as IC- agents.

Inferences drawn from the study can be summarised as follows:

1. The RHA sample used was a good Class F Pozzolan having requisite physical and chemical properties as specified in ASTM C618 and subsequently attained the target compressive strength of 60 N/mm^2.
2. The compressive strength of HPCs increased as the curing age increases for both IC-agent types and SAP contents. PHPCs and SHPCs, however, showed lower strength performance at the early ages.
3. The optimum pumice content for no adverse effect on compressive strength of the RHA based HPC is 7.5% b_{wocg} while the 0.2% b_{wob} was observed as optimum SAP content. SHPC1 (at 0.2% b_{wob} SAP content) proved as the best internally cured HPC for early age strength and showed similar long-term strength values as $PHPC_{1\&2}$.
4. Both pre-soaked pumice (up to 7.5% b_{wocg}) and SAP (0.2% b_{wob}) as IC-agent gave strength of similar values as the RHA based HPCs without the IC-agents. The comparable compressive strength recorded between 56–120 curing days' shows the long-term strength as the actual properties of the tested concrete. The long-term strength gain can be ascribed to the latter release of water by the IC agents furthering reactions of the pozzolanic material (RHA), which is augmented by internal curing delivered by pumice and SAP.
5. SAP content of 0.2% b_{wob} and saturated pumice content up to 7.5% b_{wocg} are recommended for use as IC-agent in HPC at no strength loss.

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