

Effect of Glass Waste Powder on the Compressive Strength and Permeation Properties of Concrete Containing Portland Cement and Sawdust Ash

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Abstract

The paper investigated the effect of Glass Waste Powder (GWP), as a ternary cement component on the compressive strength and permeation resistance of Portland cement (PC) and sawdust ash (SDA) blended cement concrete. Compressive strengths up to 28 days and void content and initial surface absorption after 10 minutes (ISAT-10) up to 90 days at the total replacement levels of up to 30% were determined and compared with the values obtained for conventional concrete. Seven concrete mix combinations were examined at the water/cement (w/c) ratios of 0.35, 0.50 and 0.65 and at 28-day strengths of 35-40 N/mm². At the same w/c ratios, compressive strength decreased and void content and ISAT-10 increased with increasing content of SDA and GWP. A unit replacement of PC with SDA reduced strength by 1.06% while a unit replacement of SDA with GWP, as a ternary cement component, increased strength by 1.64%. Similarly, a unit of SDA increased void content and ISAT-10 by 0.95 and 1.01% respectively while a unit of GWP as a ternary cement component reduced void content and ISAT-10 by 0.84 and 0.94% respectively. At same strengths, all the binary and ternary cement concretes possess higher resistance to permeation than the 100% PC concrete. At equal performance level, the ternary cement concretes possess higher permeation resistance than the binary cement concretes. The paper concluded that GWP, as a ternary cement component, improved the strength and permeation resistance of SDA binary cement concrete.

Keywords: absorption, compressive strength, concrete, glass waste powder, permeation, sawdust powder

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1. Introduction

The reports submitted by the Intergovernmental Panel on Climate Change have shown that increasing level of emissions into the atmosphere has a devastating effect on the environment. Hence, in order to reduce the consumption of Portland cement (PC) and reduce the emissions linked with its production, the use of by-products of industrial wastes such as silica fume, fly ash, metakaolin and ground granulated blast furnace slag as supplementary cementitious materials to partly replace the Portland cement content of concrete has been found worthwhile (BS EN 197- 1, 2000; BS EN 206- 1, 2000; BS 8500- 1, 2006, & BS 8500- 2, 2006). Supplementary Cementitious Materials (SCMs) undergo pozzolanic reaction and are characterized by low early-age performance which could be improved if appropriately mixed in the right proportion as binary or ternary blends with Portland cement (Wild *et al.*, 1996; Thomas *et al.*, 1999; Bai *et al.*, 2000; Hassan *et al.*, 2000; Poon *et al.*, 2006; Radlinski & Olek, 2012; Folagbade, 2014; Folagbade & Newlands, 2014a; Folagbade, 2017). For example, due to their higher silica content and fineness, the addition of small quantities of metakaolin and silica fume as ternary cement components would improve the performance of fly ash binary cements at early ages (Folagbade, 2014; Folagbade & Newlands, 2014a; Folagbade, 2017).

Various studies have also supported, among others, the use of by-products of agricultural wastes like rice husk ash (Zhang & Malhotra, 1996; Coutinho, 2003 & Nehdi *et al.*, 2003), corncob ash (Adesanya & Raheem, 2009, 2010; Akinwumi & Aidomojie, 2015), cassava peels ash (Ogunbode & Akanmu, 2012) and sawdust ash (Udoeyo & Dashibil, 2002; Elinwa & Ejeh, 2004; Raheem *et al.*, 2017) as possible SCMs. The studies also concluded that these by-products would reduce concrete strength at early ages due to delayed pozzolanic reaction. In order to support its use, the focus of this paper is to provide information on how the strength and durability performance of sawdust ash concrete could be improved.

Sawdust is an agricultural waste found in great quantity in Nigeria and many countries of the world. Despite being used domestically, the level of sawdust waste is still high (Oluoti *et al.*, 2014). Sawdust ash (calcined sawdust) would reduce concrete performance at early ages and its continued pozzolanic reaction with increasing curing age would improve its strength and durability performance at later ages (Obilade, 2014; Folagbade & Aluko, 2019). Also, if blended in the right proportion, SDA binary cement concrete would have good strength properties, dense microstructure and improved resistance to permeation (Folagbade & Aluko, 2019). Hence, in order to ensure good results, Folagbade & Aluko (2019) suggested an SDA content of not more than 20% in concrete. Furthermore, Elinwa *et al.* (2005) suggested that the performance of sawdust ash could be improved by

adding small quantities of SCMs with higher silica content. With this improvement, it is also possible that SDA content of more than 20% could be used in concrete to further reduce the Portland cement content and increase the environmental compatibility of concrete.

Glass powder, a good source of silica, will undergo pozzolanic reaction to produce strong, durable, cheap and environmentally compatible concrete when used at 20-30% content to partly replace Portland cement (Shayan & Xu, 2006; Maraghechi *et al.*, 2014; Rashed, 2014); Sadiqul Islam *et al.*, 2017). However, for an optimum result, a replacement level of 10% glass powder has been suggested (Sadiqul *et al.*, 2017). Also, in order to prevent concrete from cracking due to alkali-silica reaction concrete, the particle size of glass powder should not exceed 300 μ m (Ke *et al.*, 2018). From the foregoing, the blending of SDA and GWP could permit the use of higher contents of SCMs and make the blended cement concrete more economic and environmentally compatible than the conventional PC concrete at equal strength and durability levels. This is because the comparatively lower embodied energy of SDA and GWP than that of Portland cement clinker would make the ternary blended cement to be cheaper and more environmentally compatible than PC.

A good concrete is expected to be strong and durable. Also, while the strength of concrete is assessed with the aid of its compressive strength, its durability in aggressive media will depend on its permeation resistance. Hence, this paper investigated the strength development, void content and initial surface absorption (ISAT) of the ternary cement concrete. This is because while void content would measure the porosity, ISAT would measure the water absorption capacity of the surface zone of concrete which could be used to assess its resistance to permeation and its ability to protect the embedded reinforcing steel against corrosion. Hence, the results will provide more information on the suitability of the ternary cement concrete as a construction material.

2. Experimental Materials and Methods

The cements used in the experiments are ordinary Portland cement (PC), sawdust ash (SDA) calcined at a temperature of 500°C and glass waste powder (GWP) ground in a ball mill. The oxide compositions of PC, SDA and GWP are given in Table 1 and the grading curves are presented in Figure 1. SDA was used to replace PC at 20 and 30% contents to form binary cement combinations. GWP was used to replace the SDA contents of the binary cements at 5 and 10% contents to form the ternary cement combinations. The content of GWP was limited to 10% for optimum result (Sadiqul Islam *et al.*, 2017) and the particle size was limited to a maximum of 300 μ m to mitigate alkali-silica reaction (Ke *et al.*, 2018). The aggregates used are sand (with a specific gravity of 2.63) as fine aggregates and granite (with a specific gravity of 2.80) as coarse aggregates. Concrete design was based on the Building Research Establishment Design Guide (Teychenne *et al.*, 1997) and investigated at the water/cement ratios of 0.35, 0.50 and 0.65 using a free water content of 210 kg/m³. Mapefluid N200, a superplasticiser conforming to BS EN 934-2 (2009), was used during mixing to obtain a consistence class of S2 characterised by a slump of between 50 and 90 mm (BS EN 206- 1, 2000).

Table 1: Oxide compositions of Portland cement, sawdust ash and glass waste powder

Elemental Oxide (%)	PC	SDA	GWP
SiO ₂	20.36	68.71	70.03
Al ₂ O ₃	5.67	4.54	2.16
Fe ₂ O ₃	2.92	2.05	0.71
CaO	63.17	9.48	11.51
MgO	1.88	4.13	2.76
SO ₃	2.86	1.07	0.12
K ₂ O	0.78	2.45	0.66
Na ₂ O	0.24	0.06	11.42
P ₂ O ₅	-	-	0.05
TiO ₂	-	-	0.09
CaCO ₃	-	4.80	-
Cr ₂ O ₃	-	-	0.11
LOI	2.12	2.71	0.38
SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃		75.30	72.90

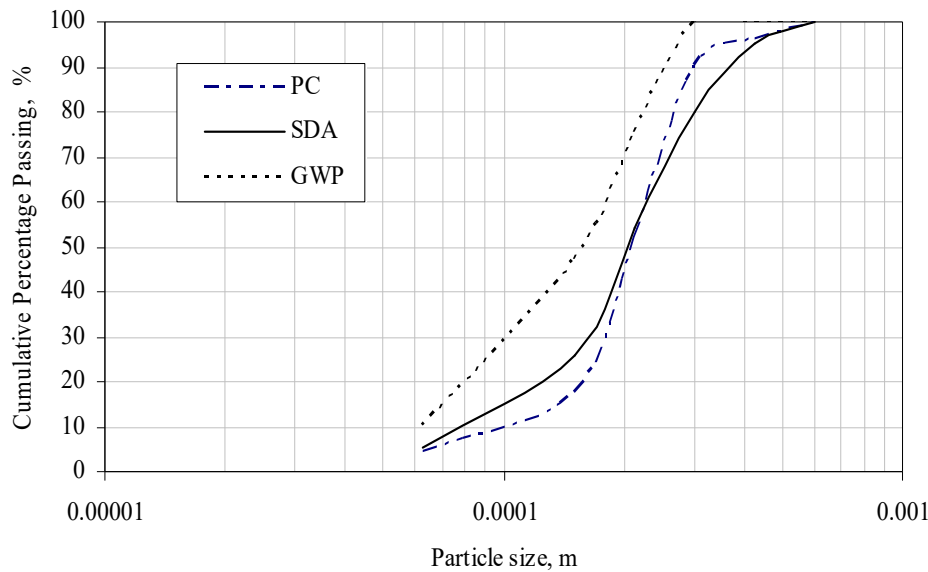


Figure 1: Grading curves of cements

Concrete was prepared to standard (BS EN 12390- 2, 2000), placed and stored under polythene for about a day and demoulded and cured in water. Compressive strength, void content and initial surface absorption tests were performed on the hardened concrete specimens. Compressive strength was determined to standard (BS EN 12390- 3, 2002) using 100 mm cubes at the curing ages of 7, 14, 21 and 28 days. Void content was determined at the curing ages of 28, 60 and 90 days in line with ASTM C642 (2006) using Equation 1. This involved determining mass of specimen oven-dried to constant mass at $105\pm 5^{\circ}\text{C}$ (A), mass of specimen after immersion to constant mass in water and boiling (B) and apparent mass of specimen after immersion, boiling and suspension in water (C).

$$\text{Void content (\%)} = \frac{B - A}{B - C} * 100 \quad (1)$$

Initial surface absorption after 10 minutes (ISAT-10) was determined at 28, 60 and 90 days in line with standard (BS 1881- 208, 1996) using 150 mm concrete cubes dried to constant mass at a temperature of $105\pm 5^{\circ}\text{C}$. This is because ISAT-10 is sufficient for assessing the effect of absorption due to driving rain on the surface of concrete (BS 1881- 208, 1996). After oven-drying and cooling, the specimens were exposed to a pressure of 200 mm head of water (Figure 2). Tap was turned off after 10 minutes of contact with water to stop the applied pressure and ISAT-10 was obtained as the product of scaled divisions moved by water in a minute along the capillary tube and the calibration factor of the capillary tube (Equation 2).

$$\text{ISAT-10} = \text{SD} \times \text{CF} \quad (2)$$

ISAT-10 = Initial surface absorption of concrete 10 minutes after water first touched its surface.

SD = Scaled divisions moved by water, in a minute, after tap was turned off.

CF = Calibration factor of capillary tube determined to standard (BS 1881- 208, 1996).

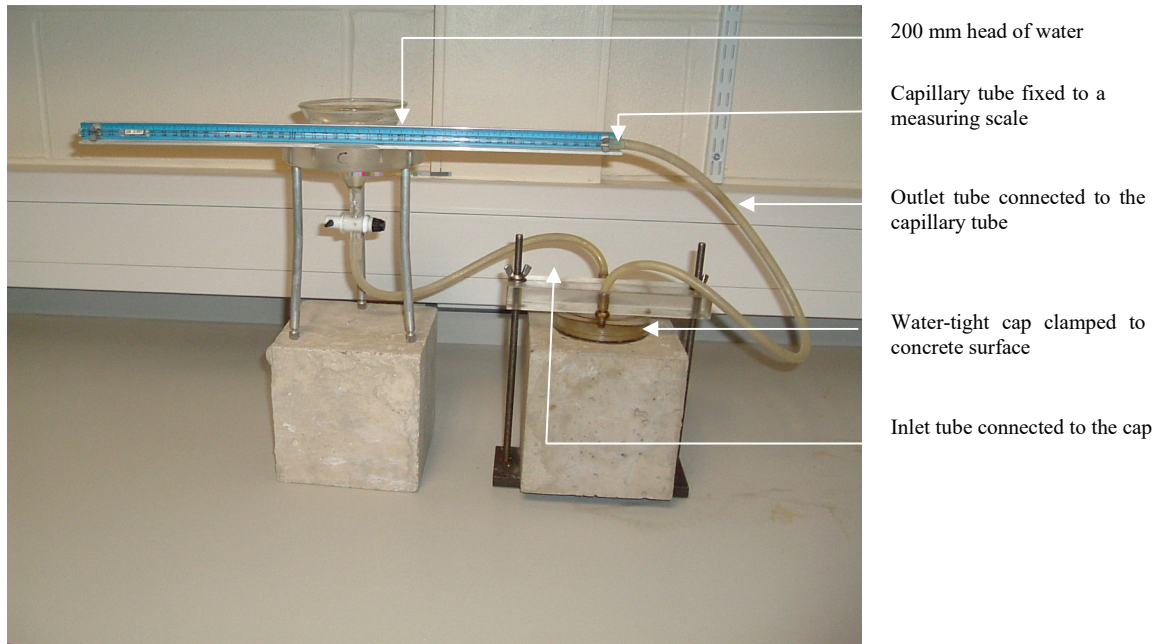


Figure 2: ISAT installation

3. Results and Discussion

The results of the compressive strength, void content and initial surface absorption after 10 minutes (ISAT- 10) of concrete at different contents of sawdust ash (SDA) and glass waste powder (GWP), water/cement ratios and 0.65 and ages up to 28 days are presented and compared. Compressive strength was compared at equal water/cement ratios while void content and ISAT- 10 were compared at equal water/cement ratios, equal 28-day strengths and equal performance levels.

3.1 Compressive Strength of Concrete

The compressive strength of concrete at different contents of sawdust ash (SDA) and glass waste powder (GWP), water/cement ratios and 0.65 and ages up to 28 days are presented in Table 2. In line with previous studies, compressive strength increased with increasing curing age (due to the formation of more strength enhancing hydration products) and reduced with increasing water/cement ratio (due to dilution effect caused by reduction in the quantity of cement). Hence, the strength factors of the cement combination concretes increased with increasing curing age. Also, the reduction in the disparities between the strength factors of the cement combination concretes and that of the 100PC concrete, with increasing curing age, further confirms the pozzolanicity of SDA and GWP and the ability of the supplementary cementitious materials to support later-age strength development.

Table 2: Compressive strengths of concretes

Mix	w/c	Compressive strength, N/mm ²				Strength factor, %				Average	
		d7	d14	d21	d28	d7	d14	d21	d28	d28	Red ^a
100PC	0.35	30.0	39.0	45.0	51.0	100	100	100	100	100	-
	0.50	23.0	31.0	36.5	41.0	100	100	100	100		
	0.65	19.5	28.5	33.0	37.0	100	100	100	100		
80PC +20SDA	0.35	22.0	29.5	35.0	40.5	73.3	75.6	77.7	79.4	78.6	21.4
	0.50	17.0	23.5	28.0	32.0	73.9	75.8	76.7	78.0		
	0.65	14.5	21.5	25.5	29.0	74.4	75.4	77.3	78.4		
80PC +15SDA +5GWP	0.35	24.5	32.5	39.0	45.0	81.7	83.3	86.7	88.2	87.9	12.1
	0.50	19.0	26.0	31.5	36.0	82.6	83.9	86.3	87.8		
	0.65	16.0	24.0	28.5	32.5	82.1	84.2	86.4	87.8		
80PC +10SDA +10GWP	0.35	26.5	35.0	41.0	47.5	88.3	89.7	91.1	93.1	93.4	6.6
	0.50	20.5	28.0	33.5	38.5	89.1	90.3	91.8	93.9		
	0.65	17.5	26.0	30.5	34.5	89.7	91.2	92.4	93.2		
70PC +30SDA	0.35	19.0	25.5	30.0	35.0	63.3	65.4	66.7	68.6	68.6	31.4
	0.50	14.5	20.0	24.5	28.0	63.0	64.5	67.1	68.3		
	0.65	12.5	18.5	22.0	25.5	64.1	64.9	66.7	68.9		
70PC +25SDA +5GWP	0.35	21.5	29.0	34.0	39.0	71.7	74.4	75.6	76.5	76.8	23.2
	0.50	16.5	23.0	27.5	31.5	71.7	74.2	75.3	76.8		
	0.65	14.0	21.0	25.0	28.5	71.8	73.7	75.8	77.0		
70PC +20SDA +10GWP	0.35	23.0	31.5	37.0	43.0	76.7	80.8	82.2	84.3	84.1	15.9
	0.50	17.5	25.0	30.0	34.5	76.1	80.6	82.2	84.1		
	0.65	15.0	23.0	27.0	31.0	76.9	80.7	81.8	83.8		

^a %Reduction in average strength factor with respect to 100PC at 28 days

The partial replacement of PC with SDA resulted in concrete with reduced compressive strength. This observation is supported by Raheem *et al.* (2017) and Folagbade (2018). Compared with 100PC concrete, the 28 day compressive strength reduced with increase in the content of SDA, as a binary cement component, by 21.4 and 31.4% at 20 and 30% contents of SDA; resulting in strength reductions of 1.07 and 1.05% respectively (with a mean of 1.06%) for a unit replacement of PC with SDA. Also, compared with the SDA binary cement concretes, the addition of 5% GWP as a ternary cement component increased the 28 day strength by 9.3% (21.4 minus 12.1) and 8.2% (31.4 minus 23.2) at the total replacement levels of 20 and 30% respectively. These resulted, respectively, in strength increases of 1.86 and 1.64% (with a mean of 1.75%) for a unit replacement of SDA with GWP. Similarly, the addition of 10% GWP as a ternary cement component resulted in strength increases of 14.8% (21.4 minus 6.6) and 15.5% (31.4 minus 15.9) at the total replacement levels of 20 and 30% respectively. These also resulted, respectively, in strength increases of 1.48 and 1.55% (with an average of 1.52%) for a unit replacement of SDA with GWP. Combining the results at the two levels of total replacement, a unit replacement of SDA with GWP resulted in strength increases of 1.52 and 1.75% (with an average of 1.64%). Hence, GWP as a ternary cement component could be used to improve the strength development of SDA binary cement concrete. This result is also supported by Khatib *et al.* (2012).

3.2 Void Content and initial Surface Absorption of Concrete at different Water/Cement Ratios

Figures 3-8 present the void content and initial surface absorption of concrete at different curing ages and water/cement ratios and different contents of SDA and GWP. As expected, the Figures show that void content and initial surface absorption of concrete reduced with curing age as a result of refinement of pore structure by hydration products; and increased with increase in water/cement ratio due to reduction in the content of the cements.

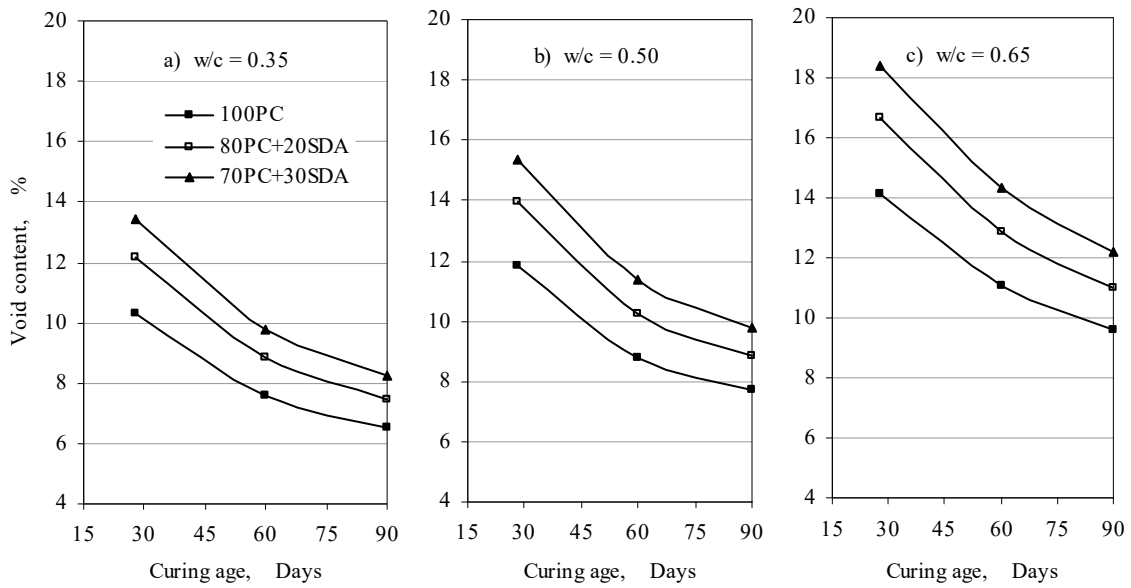


Figure 3: Void content of PC and SDA blended cement concretes

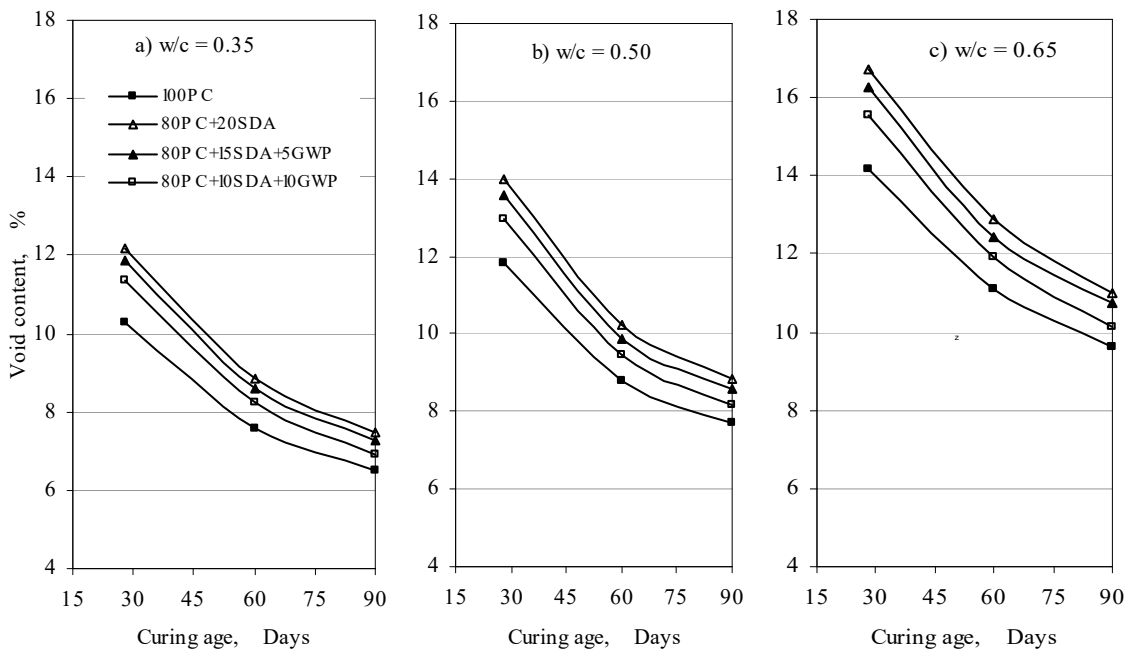


Figure 4: Void content of concrete at 20% total replacement level

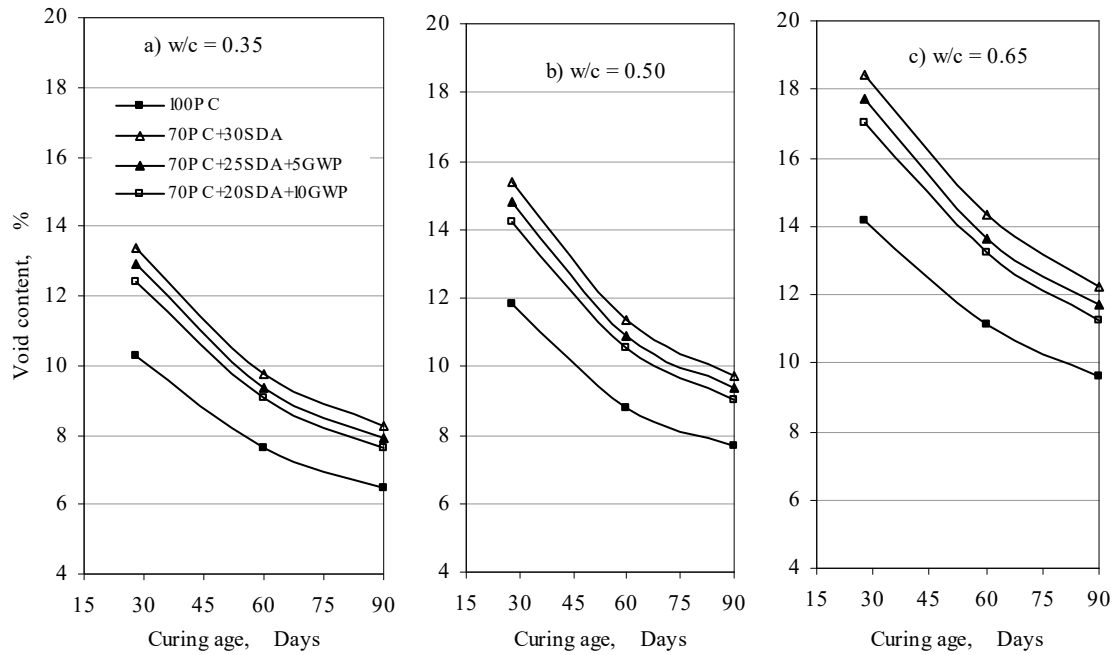


Figure 5: Void content of concrete at 30% total replacement level

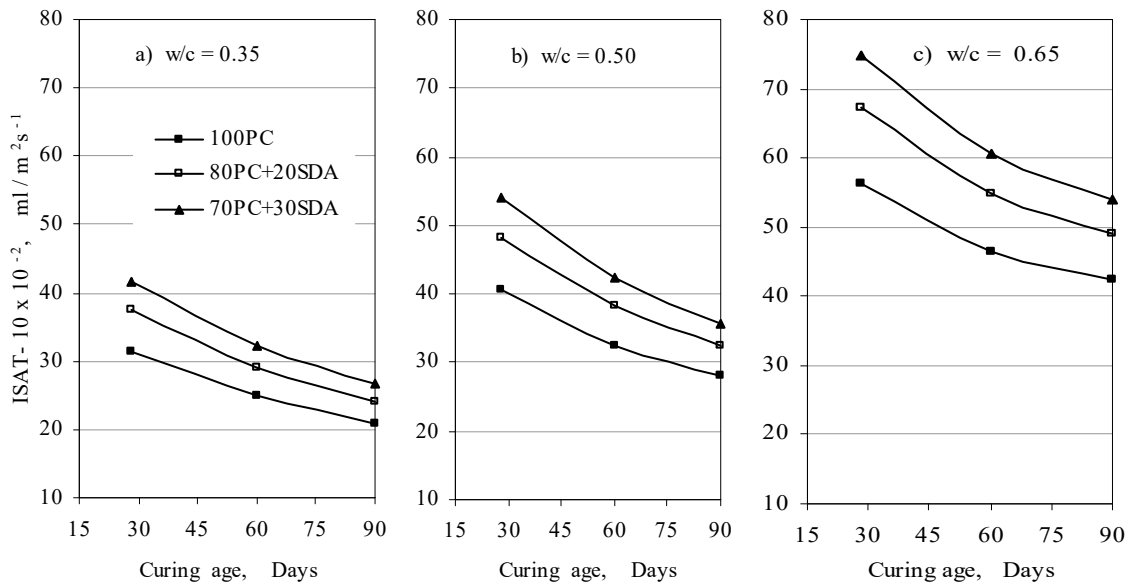


Figure 6: Initial surface absorption of PC and SDA blended cement concretes

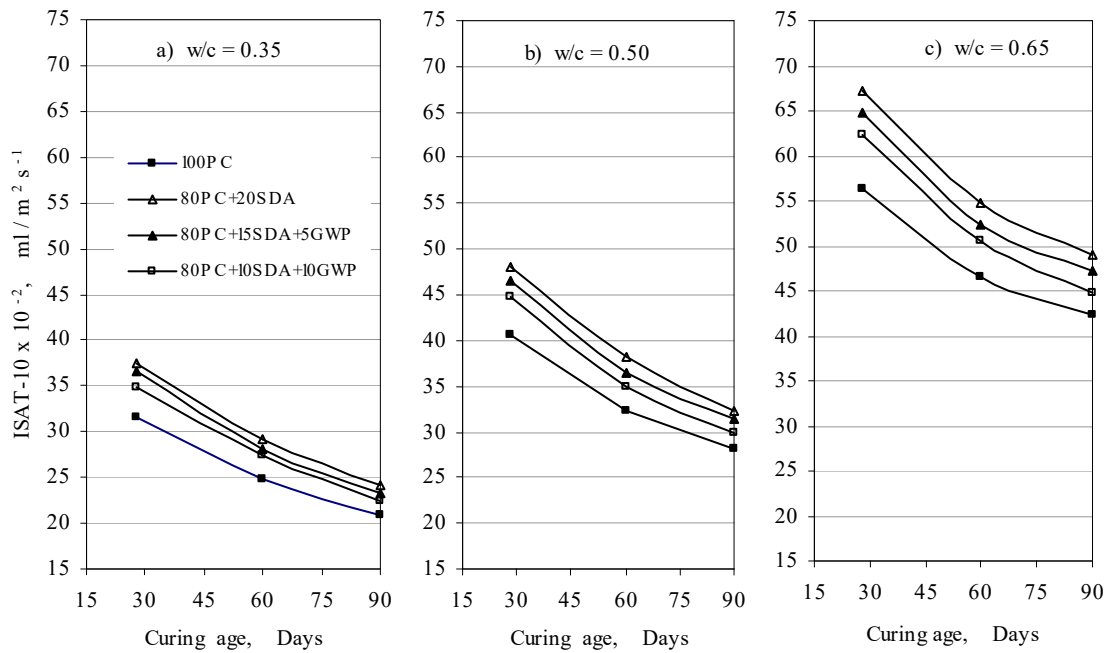


Figure 7: ISAT-10 of concrete at 20% total replacement level

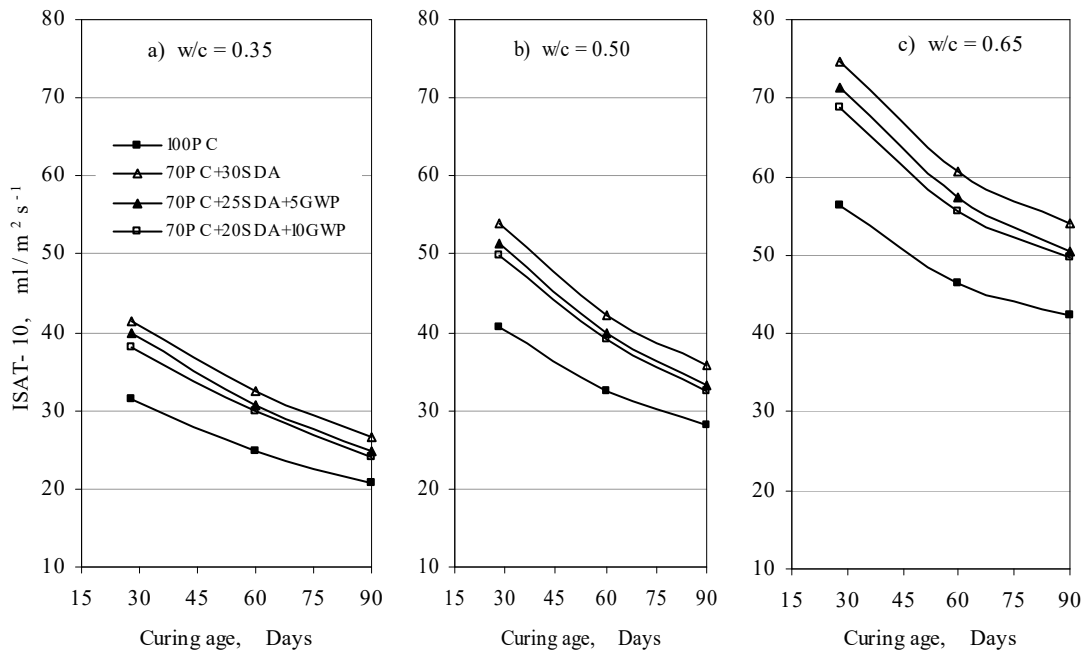


Figure 8: ISAT-10 of concrete at 30% total replacement level

The Figures also show that, at equal ages and water/cement ratios, void content and initial surface absorption increased with increase in the content of SDA as a binary cement component and reduced with increase in the content of WGP as a ternary cement component. According to Folagbade & Aluko (2019), the increase in ISAT-10 with increase in SDA would be caused by the decrease in the content of Portland cement, Ca(OH)_2 and pozzolanic reaction of SDA and the consequent reduction in the development of sufficient hydration products and less permeable microstructure. The reduction in void content and initial surface absorption with increase in the content of GWP, as a ternary cement component, would be due to its higher silica (SiO_2) content resulting in more hydration products (Table 2). This is because silica in glass powder will react with Ca(OH)_2 to produce more calcium silicate hydrate gel that would reduce void content (Ke *et al.*, 2018) and therefore reduce the initial surface absorption of the ternary cement concrete.

Table 3 presents the analysis of the 28-day void content and ISAT-10 of the concretes. The void content factors and the ISAT-10 factors respectively measure the differences between the 28-day void content and ISAT-

10 of the 100PC concrete and the blended cement concretes at different water/cement ratios. The Table shows that the 28-day void content of concrete increased respectively by 18.0 and 30.1% at 20 and 30% contents of SDA resulting in percentages of increase in void content of 0.90 and 1.00 respectively (with a mean of 0.95%) for a unit replacement of PC with SDA. With the addition of 5% GWP, as a ternary cement component, the 28-day void content reduced by 2.9 and 4.9% at the total replacement levels of 20 and 30% respectively. These resulted respectively in void content reduction percentages of 0.58 and 0.98 (with a mean of 0.78%) for a unit replacement of SDA with GWP. Similarly, the addition of 10% GWP as a ternary cement resulted in void content reductions of 8.0 and 9.8% at the total replacement levels of 20 and 30% respectively. These also resulted respectively in void content reduction percentages of 0.80 and 0.98 (with a mean of 0.89%) for a unit replacement of SDA with GWP. Hence, combining the two total replacement levels, a unit replacement of SDA with GWP resulted in a void content reduction of 0.78-0.89% (with an average of 0.84%).

Table 3: Analysis of 28-Day void content and ISAT-10 of concretes

Mix	W/C	28-Day void content			28-Day ISAT- 10		
		Void content, %	VCF ^{a)} , %	Average VCF, %	ISAT-10 x 10 ⁻² , ml/m ² s ⁻¹	ISAT-10 factor ^{b)} , %	Average ISAT-10 factor, %
100PC	0.35	10.30	100		31.5	100	
	0.50	11.82	100	100	40.7	100	100
	0.65	14.15	100		56.4	100	
80PC +20SDA	0.35	12.16	118.0		37.4	118.7	
	0.50	13.96	118.1	118.0	48.1	118.2	118.7
	0.65	16.70	118.0		67.2	119.2	
80PC +15SDA +5GWP	0.35	11.85	115.1		36.5	115.9	
	0.50	13.59	115.0	115.1	46.5	114.3	115.0
	0.65	16.28	115.1		64.7	114.7	
80PC +10SDA +10GWP	0.35	11.35	110.2		34.9	110.8	
	0.50	12.98	109.8	110.0	44.8	110.1	110.5
	0.65	15.56	110.0		62.3	110.5	
70PC +30SDA	0.35	13.40	130.1		41.5	131.8	
	0.50	15.38	130.1	130.1	54.0	132.7	132.3
	0.65	18.42	130.2		74.7	132.5	
70PC +25SDA +5GWP	0.35	12.91	125.3		39.8	126.4	
	0.50	14.80	125.2	125.2	51.5	126.5	126.5
	0.65	17.72	125.2		71.4	126.6	
70PC +20SDA +10GWP	0.35	12.38	120.2		38.2	121.3	
	0.50	14.21	120.2	120.2	49.8	122.4	122.0
	0.65	17.01	120.2		68.9	122.2	

^{a)} Void content factor (VCF)- Ratio of void content of concrete to that of 100PC concrete

^{b)} ISAT-10 factor- Ratio of ISAT-10 with respect to the 100PC concrete

The 28-day ISAT-10 of concrete increased respectively by 18.7 and 32.3% at 20 and 30% contents of SDA resulting in percentages of increase in ISAT-10 of 0.94 and 1.08 respectively (with a mean of 1.01%) for a unit replacement of PC with SDA. With the addition of 5% GWP, as a ternary cement component, the 28-day ISAT-10 reduced by 3.7 and 5.8% at the total replacement levels of 20 and 30% respectively. These resulted respectively in ISAT-10 reduction percentages of 0.74 and 1.16 (with a mean of 0.95%) for a unit replacement of SDA with GWP. Similarly, the addition of 10% GWP as a ternary cement resulted in ISAT-10 reductions of 8.2 and 10.3% at the total replacement levels of 20 and 30% respectively. These also resulted respectively in ISAT-10 reduction percentages of 0.82 and 1.03 (with a mean of 0.93%) for a unit replacement of SDA with GWP. Hence, combining the two total replacement levels, a unit replacement of SDA with GWP resulted in ISAT-10 reduction of 0.93-0.95% (with an average of 0.94%). Therefore, GWP as a ternary cement component could be used to reduce the void content and initial surface absorption and increase the permeation resistance and durability of SDA blended cement concrete.

3.3 Void Content and initial Surface Absorption of Concrete at Equal 28-Day Strengths

The specification of structural concrete is based on the 28-day strengths. Hence, in order to assess the permeation resistance of the concretes at equal 28-day compressive strengths, the 28-day compressive strengths in Table 2 and the 28-day void content and ISAT-10 values in Table 3 have been interpolated over the water/cement ratios. Hence, Table 4 presents the water/cement ratios at which the 28-day strengths of 35-40 N/mm² were achieved by the blended cement concretes and the corresponding void content and ISAT-10 values at these strengths. Table 4

reveals that equal strengths with 100PC concrete were attained by the blended cement concretes at lower water/cement ratios. The implication of this is that higher cement content would be required by the blended cement concretes to achieve equal strengths with the conventional 100PC concrete. Comparatively, at equal total replacement levels, the SDA binary cement concretes would require lower water/cement ratios than the ternary cement concretes to achieve equal strengths with the 100PC concrete. Also, the water/cement ratios required to achieve equal strengths with the 100PC concrete decreased with increase in the content of SDA as a binary cement component and increased with increase in the content of GWP as a ternary cement component. The implication of this is that more cement content will be required by the SDA binary cement concretes than the corresponding GWP ternary cement concretes at equal strengths. This result is supported by Folagbade & Newlands (2014b) and Folagbade & Aluko (2019). The foregoing also supports the propensity of GWP to support compressive strength development than SDA.

Table 4: Void content and ISAT-10 at equal 28-day strengths of concrete

Mix combination	Compressive strength at 28 days								
	35 N/mm ²			37 N/mm ²			40 N/mm ²		
	w/c	VC ^{a)}	ISAT ^{b)}	w/c	VC ^{a)}	ISAT ^{b)}	w/c	VC ^{a)}	ISAT ^{b)}
100PC	*	*	*	0.65	14.15	56.4	0.52	12.08	42.4
80P+20SDA	0.43	13.00	42.1	0.40	12.66	40.0	0.35	12.16	37.4
80PC+15SDA+5GWP	0.52	13.89	48.5	0.47	13.17	43.8	0.42	12.54	40.2
80PC+10SDA+10GWP	0.61	14.78	56.9	0.53	13.42	47.7	0.46	12.45	41.4
70PC+30SDA	0.35	13.40	41.5	x	x	x	x	x	x
70PC+25SDA+5GWP	0.41	13.54	43.5	0.38	13.21	41.5	x	x	x
70PC+20SDA+10GWP	0.48	13.91	47.8	0.44	13.36	44.3	0.39	12.77	40.6

a) Void content (%)

b) ISAT-10 x 10⁻², (ml / m² s⁻¹)

* The required water/cement ratio is higher than 0.65

x The required water/cement ratio is lower than 0.35

Table 4 shows that void content and ISAT-10 of concrete reduced with increase in compressive strength. Also, all the binary and ternary cement concretes at up to 30% total contents of SDA and GWP have lower void contents and ISAT-10 values and would therefore have higher resistance to permeation than the 100PC concrete at equal strengths. This observation is supported by Dhir & Byars (1991), Dias *et al.* (2003), Folagbade (2016, 2017) and Folagbade & Aluko (2019) which show that blended cement concretes have the tendency to perform better than the conventional Portland cement concrete at equal strengths. Furthermore, Table 4 shows that, at equal strengths, void content and ISAT-10 of concrete reduced with increase in SDA content as a binary cement component and increased with increase in GWP content as a ternary cement component. This implies that, at equal strengths, the addition of GWP as a ternary cement component would result in better strength development but not better resistance to permeation than SDA. Hence, at equal strengths, SDA would have more beneficial effect on durability than GWP when the design criterion is solely durability. However, since lower water/cement ratios and hence higher contents of cement will be required by the binary than the ternary cement concretes, the final choice will depend on the economic implication (material costs) and environmental implication (embodied carbon-dioxide contents) of the concretes at equal strengths (Folagbade, 2014; Folagbade & Newlands, 2014a,b) or at equal performance levels.

3.4 Blended Cement Concrete at Equal Performance Level

Table 5 compares the performance of the blended cement concretes by determining, within the limit of the study, the water/cement ratios at which the concrete mixes achieved equal performance with the 80PC+20SDA concrete (void content of 13.0% and ISAT-10 of 42.1 x 10⁻² ml / m² s⁻¹). The Table shows that at the two total replacement levels (20 and 30%), the ternary cement concretes require higher water/cement ratios than the binary cement concretes to achieve equal performance level of 13% void content and 42.1 x 10⁻² ml / m² s⁻¹ ISAT-10. Hence, assuming almost equal cost and embodied carbon dioxide contents for SDA and GWP, the binary cement concretes will require higher cement contents and attract higher cost and embodied carbon-dioxide contents than the ternary cement concretes. Hence, it could be concluded that the addition of GWP, as a ternary cement component would improve the strength and permeation resistance of SDA binary cement concrete.

Table 5: Blended cement concretes at equal 28-day void content and ISAT-10 performance

Mix combination	Water/Cement Ratio	
	Void Content = 13%	ISAT-10 = $42.1 \times 10^{-2} \text{ ml / m}^2 \text{ s}^{-1}$
80P+20SDA	0.43	0.43
80PC+15SDA+5GWP	0.46	0.44
80PC+10SDA+10GWP	0.50	0.46
70PC+30SDA	x	0.36
70PC+25SDA+5GWP	0.36	0.39
70PC+20SDA+10GWP	0.41	0.41

^x Water/Cement ratio is lower than 0.35

4. Conclusion

The compressive strength development, void content and initial surface absorption of concretes containing SDA and GWP as partial replacements, of up to a total content of 30%, for PC have been investigated. The following conclusions have been drawn from the study.

- Compressive strength increased with increase in curing age and reduced with increase in water/cement ratio. On the other hand, while void content and initial surface absorption reduced with increase in curing age and compressive strength, they increased with increase in water/cement ratio.
- At same water/cement ratios, compressive strength reduced and void content and initial surface absorption increased with increase in the content of SDA as a binary cement component. On the other hand, compressive strength increased and void content and initial surface absorption reduced with increasing content of GWP as a ternary cement component.
- All the binary and ternary blended cement concretes, at replacement levels up to 30%, achieved equal strengths with the conventional PC concrete at lower water/cement ratios. However, at equal total replacement levels, SDA binary cement concretes would require lower water/cement ratios and therefore more cement contents than the ternary cement concretes to achieve equal strengths.
- Also, at equal strengths, all the binary and ternary blended cement concretes have lower void content and ISAT-10 values and hence higher permeation resistance than the 100% PC concrete. Furthermore, GWP has better propensity to improve permeation resistance than SDA at equal performance levels.

Hence, for better strength and permeation resistance, the addition of GWP as a ternary cement component to the binary combination of PC and SDA content of concrete would permit the use of SDA content higher than 20% in concrete and result in structural concrete with higher permeation resistance than the 100% PC concrete.

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