Scientific paper

Mechanical Properties and Durability of Normal and Water Reduced High Strength Grade 60 Concrete Containing Rice Husk Ash

Hilmi Bin Mahmud¹, Muhammad Fakhar Abdul Malik², Rahaimi Abdul Kahar², Muhammad Fauzi Mohd. Zain³ and Sudharshan Naidu Raman⁴

Received 25 October 2008, accepted 17 January 2009

Abstract

This paper reports an investigation on the strength properties, a time dependent property as well as durability characteristics of normal and water reduced high strength concrete (WRHSC), with or without rice husk ash (RHA), designed to produce Grade 60 at 28 days. RHA was 'added' or 'replaced' at/by 5% - 20% of the cement content. A PCE superplasticizer was added to all mixes to provide workability in the range of 150 - 200 mm slump. Based on the initial trial mixes, four high strength concrete mixes were selected for further tests on mechanical properties (compressive strength, tensile splitting strength, flexural strength and static modulus of elasticity), drying shrinkage and durability (water absorption, sorptivity, chemical resistance to MgSO_4 solution). Incorporation of RHA increases the strength, reduces the drying shrinkage and improves the durability of concrete compared to conventional OPC concrete.

1. Introduction

Environmental and economic reasons require adjustments be made to the present concrete making methods. Mineral admixtures have been used successfully to partially replace energy and resources dependent portland cement. The technical advantage of using these mineral admixtures is the enhancement of many properties in the fresh and hardened states, which include lower heat of hydration, improved durability in acidic environments and higher ultimate strengths (Mehta 1987).

It is estimated that the world's annual production of rice is about 500 million tonnes, a major portion (over 90%) of which is produced in South East Asia (Cook 1996). From this amount, Malaysia produces more than 2 million tonnes, of which 20% or 400 thousand tonnes is husk and more than 90% of it is silica. Current technology points to the fact that the ash produced by burning rice husk, can be used as a supplementary cementitious material in concrete (Mehta and Folliard 1994). Under controlled burning and after grinding to a specified fineness, the ash produced by incinerating rice husk is pozzolanic. Being a pozzolan, it will contribute to higher long term strength and improve the durability of concrete.

This paper reports the potential use of rice husk ash to produce high strength/high performance concrete (HSC/HPC) of 60 N/mm² at 28 days. The utilization of rice husk ash (RHA) to enhance the mechanical properties, durability characteristics, as well as time dependent property of concrete are attempted. Optimum 'replacement' or 'addition' of cement with RHA with regards to concrete strength will be determined. Under the influence of different curing regimes, the mechanical properties and durability of concrete with or without RHA are investigated. The beneficial effects of inclusion of RHA in concrete are clearly shown in this paper.

2. Experimental programme

2.1 Materials

Ordinary Portland cement (OPC) Type 1 from a local manufacturer was used. It has a specific gravity and specific surface of 3.12 and 3280 m²/kg respectively. Rice husk used was obtained from a typical local rice milling factory. Rice husk ash (RHA) was obtained by slow burning of the husk in a ferrocement furnace. After a cooling down period, which may take 24 hours, the ash was grind using a Los Angeles machine to achieve the required fineness standard of BS 3892. Its specific gravity, average pore size and specific surface area (determined by nitrogen absorption technique, BET) was 2.03, 4.18 nm and 23455 m²/kg. Major chemical composition of OPC and RHA are presented in **Table 1**. It shows that RHA consists of 89.87 % SiO_2 . The total sum of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ is 90.55 % and hence RHA can be classified as Class N as prescribed in ASTM C618. XRD analysis of the RHA samples shows mainly amorphous silica formation, consisting mainly of quartz mineral group as shown in **Fig. 1**. A polycarboxylic ether (PCE) superplasticizer, having specific gravity and solid content of 1.09 - 1.1 and 34%-36% respectively,

¹Professor, Department of Civil Engineering, University of Malaya, Malaysia.

E-mail: hilmi@um.edu.my

²Graduate, Department of Civil Engineering, University of Malaya, Malaysia.

³Professor, Department of Civil and Structural Engineering, University Kebangsaan Malaysia, Malaysia

⁴Ph.D candidate, Department of Civil and Environmental Engineering, University of Melbourne, Australia.

was used as the chemical admixture. For flowable high strength concrete, the new superplasticizer displayed significant advantages in workability and better consistency retention compared to other superplasticizers. Coarse aggregate was crushed granite of 20 mm maximum size, having specific gravity and water absorption

of 2.63 and 0.5% respectively. Fine aggregate used was mining sand of 5 mm maximum size having specific gravity, water absorption and fineness modulus of 2.69, 1.14% and 3.11 respectively and conformed to zone 1 of BS 882: Part 103: 1985.

Table 1 Chemical composition of OPC and RHA.

Oxide (%)	OPC	RHA
SiO ₂	21.27	89.87
Al ₂ O ₃	6.19	0.14
Fe ₂ O ₃	3.64	0.94
Total SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃	-	90.55
CaO	65.2	0.49
Na ₂ O	0.19	0.25
K ₂ O	0.71	2.16
LOI	1.53	4.81

Fig. 1 XRD analysis of RHA.

2.2 Mixture proportioning, mixing and tests

The mixes were designed to achieve concrete of grade 60 N/mm² at 28 days. Mixture proportioning was based on the D.O.E mix design method (DOE 1975). Using this method, a control concrete containing superplasticizer (Mix NC1) was designed with w/c of 0.38 to provide Grade 60 concrete (Table 2). Another control mix of w/c of 0.50 (Mix NC2) was initially designed for 40 N/mm². The water content of this mix was reduced by 28% to produce high strength water reduced concrete (WRC) of 0.36 w/c. To evaluate the effects of the method of incorporation of RHA on the properties of fresh and hardened concrete of these water reduced mixes, 5%, 10% 15% and 20% of the cement content was 'added' or 'replaced' by RHA. For the normal concrete mixes (w/c of 0.38), only the effect of cement replacement by RHA was conducted. Using varying amounts of the PCE superplasticizer, all the mixes were designed to produce slump in the range of 150 – 200 mm. The mixture proportions for all mixes are shown in Table 2. The compressive strength of all these mixtures, subjected to continuous water curing, is presented in Table 3.

Based on the results from the above trial mixes, four high strength concrete (HSC) mixes consisting of optimum RHA 'addition' and 'replacement' water-reduced mixes, optimum normal RHA 'replacement' mix, as well as the control water-reduced mix were selected for the following investigations and tested up to 365 days.

Table 2 Mixture proportions and workability of various concrete mixes.

Mix No. *	w/b	Sp (%)	Slump (mm)	Water (kg/m ³)	Cement (kg/m ³)	RHA (kg/m ³)	FA (kg/m ³)	CA (kg/m ³)	Remarks
NC1	0.38	0.11	170	190	500	0	745	945	Normal OPC mix RHA replacement mixes
NC5R1	0.38	0.16	160	190	475	25	745	945	
NC10R1	0.38	0.22	160	190	450	50	745	945	
NC15R1	0.38	0.28	200	190	425	75	745	945	
NC20R1	0.38	0.57	200	190	400	100	745	945	
NC2	0.50	-	40	190	380	0	815	995	Grade 40 mix Water reduced mixes RHA replacement mixes
WRNC2	0.36	0.30	160	137	380	0	868	995	
WR5R2	0.36	0.55	180	137	361	19	868	995	
WR10R2	0.36	0.60	170	137	342	38	868	995	
WR15R2	0.36	0.90	180	137	323	57	868	995	
WR20R2	0.36	1.15	200	137	304	76	868	995	
WR5A2	0.36	0.54	180	144	380	19	863	974	Water reduced mixes RHA addition mixes
WR10A2	0.36	0.64	200	150	380	38	852	960	
WR15A2	0.36	0.88	200	157	380	57	839	947	
WR20A2	0.36	1.02	180	164	380	76	827	933	

*NC and WR denote normal and water reduced concrete and A and R denote RHA 'addition' or 'replacement' of cement.

(1) Mechanical properties

- Compressive Strength on 100 x 100 x 100 mm cubes (BS1881: Part 116: 1983)
- Tensile Splitting Strength on 150 mm dia. x 300 mm cylinders (BS 1881: Part 117: 1983)
- Flexural Strength on 100 x 100 x 500 mm prisms (BS 1881: Part 118: 1983)
- Static Modulus of Elasticity on 150 mm dia. x 300 mm cylinders (BS 1881: Part 121: 1983)

All specimens were subjected to air-drying and water curing conditions until the age of testing.

(2) Time dependent property

- Drying shrinkage on 150 mm dia. x 300 mm cylinders (ASTM C 531-85)

Specimens were subjected to air-drying or initial 28 days water curing conditions and tested up to 1 year.

(3) Durability

- Water absorption on 100 mm dia. x 200 mm cylinders. The specimens were immersed in water for 96 hours (Abdul Razak *et al.* 2004). The percentage weight of absorption was determined at the end of the immersion period. Test was conducted at 28 and 90 days. The specimens were subjected to air drying or water curing conditions. Prior to test, specimens were conditioned in an oven for 72 hours.
- Sorptivity on 100 mm dia. x 200 mm cylinders. Test was carried out by placing the specimens on steel rods in a tray. To permit free water movement, the bottom surface of the specimens was in contact with water, of up to a height of 5 mm. The uptake of water by capillary suction was measured through mass of the specimen at intervals of 5, 10, 60, 120 and 240 minutes (Güneyisi and Mermedas 2007). This test was conducted at 28 and 90 days, subjected to air drying or water curing regimes. Prior to test, specimens were conditioned in an oven for 72 hours.
- Sulphate resistance of concrete subjected to $MgSO_4$ solution. Specimens of 100 x 100 x 100 mm cubes and 150 mm dia. x 300 mm cylinders were subjected to air drying or initial 7 days water curing before subjected to 3 cycles of tests, each cycle consisting of 30 days immersion in $MgSO_4$ solution followed by air drying for 7 days. Tests conducted at the end of each cycle were compressive strength (100 mm cubes), length change and weight loss on 150 mm dia. x 300 mm cylinders.

3. Results and discussion**3.1 Workability**

Workability of concrete can be defined as the ease to be transported, placed and consolidated without excessive bleeding or segregation (Tam 2003). In this study, different dosages of superplasticizer (Sp) were added to different mixtures in order to maintain the required workability of 150 – 200 mm slump, as shown in **Table**

2. It is observed that dosage of Sp is inter-related with w/b ratio, the lower the ratio, the higher the dosage required for similar workability. To attain the desired workability for RHA concrete, the required dosage was in the range of 0.16 % to 1.15% of the binder content. In general, with the exception of mixes WR10R2 and WR10A2, for similar workability, Sp dosage for RHA addition mixes were marginally lower than the replacement mixes because the RHA total binder ratio is higher for the later. Inclusion of RHA, either as 'addition' or 'replacement' of cement demand higher Sp when compared to the control WRNC2 mix. For both the normal and water reduced 'replacement' mixes, the Sp dosage increase with increasing RHA content. This is due to higher surface area and water absorbing characteristic of the RHA.

At the same RHA content of 20% by weight of cement, RHA 'addition' mixes decreased the Sp demand by about 12% compared to the RHA 'replacement' mixes. Inclusion of RHA, either as 'addition' or 'replacement' of up to 10% cement content demand higher Sp when compared to WRNC2 (100% and 113% respectively). This is due to the specific surface area of RHA which was 6-8 times larger than cement (Edi Majuar 2004). For similar workability, data showed that Sp dosage is affected by method of inclusion and percentage of RHA in the concrete mixes.

3.2 Compressive strength of trial mixes**3.2.1 Effect of RHA 'replacement' of cement**

As presented in **Table 3**, the highest strength for the normal and water reduced RHA mixes was achieved at 10% cement replacement (mixes NC10R1 and WR10R2). For 20% replacement, strength of 60 N/mm² was still attainable. Other investigators showed that the optimum replacement of cement by RHA for optimum strength is between 10% to 20% (Zhang and Malhotra

Table 3 Compressive strength for various mixes.

Mix No. *	w/b	Compressive strength N/mm ²			
		1d	3d	7d	28d
NC1	0.38	31.4	44.2	53.6	61.0
NC5R1	0.38	29.5	46.1	52.2	62.0
NC10R1	0.38	27.3	43.8	50.8	64.2
NC15R1	0.38	31.7	44.1	50.5	61.5
NC20R1	0.38	31.2	43.3	52.8	60.4
NC2	0.50	19.0	25.2	32.0	40.9
WRNC2	0.36	30.4	41.3	49.9	61.5
WR5R2	0.36	24.8	40.1	51.5	60.6
WR10R2	0.36	29.7	45.1	52.9	66.7
WR15R2	0.36	23.7	40.0	50.9	62.9
WR20R2	0.36	23.8	39.8	48.0	62.5
WR5A2	0.36	30.1	41.5	50.2	61.0
WR10A2	0.36	31.2	47.2	59.8	68.6
WR15A2	0.36	29.7	41.0	50.8	61.1
WR20A2	0.36	28.5	39.8	49.5	60.5

*NC and WR denote normal and water reduced concrete and A and R denote RHA 'addition' or 'replacement' of cement.

1996; Ismail and Waliuddin 1996). From the results obtained, all RHA normal and water-reduced 'replacement' mixtures were able to produce HSC of 60 N/mm² at 28 days. This result shows that RHA can be the alternative pozzolanic binder to produce HSC of this strength level.

3.2.2 Effect of RHA 'addition'

Table 3 also shows that for RHA addition mixes, the optimum strength resulted from 10% addition (mix WR10A2), similar to that found for grade 80 RHA concrete (Mahmud *et al.* 2002). Compared to the control WRNC2, all water reduced RHA 'addition' mixes exhibited marginally better strength at 28 days. This can be attributed to higher amount of lime (Ca(OH)₂) available for pozzolanic reaction as the cement content was not replaced (as compared to the RHA replacement mixes. Data also revealed that all RHA addition mixes were capable of achieving the target strength of 60 N/mm² at 28 days. From the data given in **Table 3**, based on their highest 28 days compressive strength, the optimum 'replacement' and 'addition' mixes, as well as the water reduced control mix (Mixes WR10R2, NC10R1, WR10A2 and WRNC2), were selected for further investigations on mechanical properties, drying shrinkage and durability.

3.3 Mechanical properties

The results of the various tests on the mechanical properties of the 4 selected concrete mixes (WRNC2, NC10R1, WR10R2 and WR10A2), taken up to 1 year, are discussed in the following sections:

3.3.1 Compressive strength

Table 4 shows that the use of 10% RHA as 'addition' or 'replacement' of cement increases the compressive strength of concrete at all ages, irrespective of type of

curing. WR10A2 mix achieved the highest strength of all the mixes. For water reduced RHA 'addition' and 'replacement' mixes, under both curing regimes, higher strengths were achieved compared to the control WRNC2 and NC10R1 mixes from 3 days onwards. This result showed that RHA can contribute to the strength development even when left to dry environment. At 28 days, all concrete achieved the target strength of 60 N/mm² regardless of curing type. Under water curing, all RHA concrete were able to achieve 70 N/mm² at 1 year. Strength ratio (ratio of air drying/water curing) for NC10R1 mix due to the effect of curing is 0.98 at 28 days and 0.89 for both 180 and 365 days. For WR10A2, the ratio is 0.98 at 28 days and 0.96 at both 180 and 365 days. As for WR10R2 mix, the strength ratio is 0.98 at 28 days and 0.92 at both 180 and 365 days. It can be suggested that that air-drying did not bring about significant reduction in strength for RHA concrete when compared to control superplasticized concrete. This may be due to the higher humidity (R.H ~ 90%) experienced in this part of the world.

3.3.2 Tensile splitting strength

The value of tensile strength is important for non reinforced concrete structures such as pavement slabs and airfield runway. These structures are designed based on bending strength rather than compressive strength (Zain *et al.* 2002). **Table 5** shows the splitting tensile strength development up to the age of 365 days. From 28 days onwards, all pozzolanic mixtures under water curing exhibited strength enhancement compared to the control. The strength ratio due to curing methods for all the concrete mixes is in the range of 0.90 to 1.03 from 28 days onwards. The ratio for all RHA concretes ranged from 0.90 to 0.95. These points to the fact that curing method does not substantially affect the splitting tensile strength of RHA concrete at all ages. The ratio of tensile splitting

Table 4 Compressive Strength for selected HSC mixes.

Mix No.	Compressive strength (N/mm ²)						Compressive strength (N/mm ²)						Air drying Water curing Strength ratio		
	Air drying						Water curing						28d	180d	365d
	1d	3d	7d	28d	180d	365d	1d	3d	7d	28d	180d	365d			
WRNC2	29.1	39.9	49.0	61.0	66.3	67.6	30.4	41.3	49.9	61.5	68.1	69.5	0.99	0.97	0.97
NC10R1	27.0	41.1	50.1	62.8	63.0	64.5	27.3	43.8	50.8	64.2	70.9	72.3	0.98	0.89	0.89
WR10R2	28.5	43.2	50.7	65.1	66.5	67.7	29.7	45.1	52.9	66.7	72.3	73.5	0.98	0.92	0.92
WR10A2	30.0	45.0	58.5	67.1	71.1	72.2	31.2	47.2	59.8	68.6	74.1	74.9	0.98	0.96	0.96
												Avg.	0.98	0.94	0.94

Table 5 Tensile Splitting Strength values for selected HSC mixes.

Mix No.	Splitting tensile strength (N/mm ²)				Splitting tensile strength (N/mm ²)				Air drying Water curing Strength ratio		
	Air Drying				Water Curing				28d	180d	365d
	7d	28d	180d	365d	7d	28d	180d	365d			
WRNC2	3.10	3.82	4.00	4.00	3.19	3.80	3.90	4.00	1.01	1.03	1.00
WR10R2	2.40	3.70	3.80	4.00	2.30	3.90	4.10	4.20	0.95	0.93	0.95
WR10A2	2.80	3.80	3.80	4.00	3.00	4.10	4.20	4.40	0.93	0.90	0.91
NC10R1	3.00	4.00	4.10	4.30	3.20	4.30	4.50	4.60	0.93	0.91	0.93

strength to compressive strength decreases with age. From **Table 6**, this ratio for all the mixtures was computed to be approximately 5.7% to 6.3% from 28 days onwards. Other reference reported that ratio of tensile splitting strength to compressive strength decrease with increasing compressive strength; (8% - 9%) for medium strength and 7% for high strength concrete (Mehta and Monteiro 1993).

3.3.3 Flexural strength

Data on the flexural strength of the 4 selected HSC mixes are presented in **Table 7**. Results showed that all concrete mixes achieve higher modulus under water curing. Flexural strength at 28 days was in the order of 6.5 N/mm² to 7.6 N/mm² for all mixes, irrespective of type of curing. Beyond 28 days, the mixtures did not show any significant strength increase. However unlike splitting tensile strength, all blended mixtures attained higher flexural strength compared to the control. The NC10R1 mixture recorded the highest flexural strength compared to the other mixes. From the results shown, incorporation of the pozzolanic material RHA significantly increases the flexural strength while marginally improve the tensile splitting strength. From **Table 8**, the ratio of air drying to water curing strengths varies from 0.95 to 0.99 at all the ages. As mentioned before, the presence of the high humidity in the country may have affected favorably to the air dried specimens.

3.3.4 Static modulus of elasticity

The development of static modulus of elasticity in compression with age for all mixtures is presented in **Table 9**. At 28 days, all mixtures recorded stiffness values in the range of 23.4 - 30.7 kN/m², irrespective of type of curing. The table also shows that from 28 days onwards, all RHA mixes exhibited higher modulus of elasticity than the control concrete, irrespective of curing regime. The results indicate that generally as the concrete strength increases, so does the modulus of elasticity,

although the rate of increase is less compared to the rate of increase in strength. This result infers that the modulus of elasticity of RHA concrete is affected by the method of inclusion of RHA, curing method or age.

Blended mixtures only show clear indication of enhancement in stiffness compared to the control mixtures at a much later age i.e. 180 days compared to the compressive and tensile strengths which occur at 7 days. According to (Iravani 1999), modulus of elasticity of concrete is also affected by method of curing, chemical admixture, supplementary cementitious materials, specimen size, age of concrete and coarse aggregate. It is observed that the incorporation of pozzolan only improved stiffness slightly and no significant changes were noted beyond 180 days. At 180 days WR10R2, WR10A2 and NC10R1 mixtures showed an average of 18.2 % increase in elastic modulus; whereas the WRNC2 mixture achieved an 18% increase. Even though the modulus of elasticity increased with increasing compressive strength, its strength development is gradually lower than that of compressive strength. At a specified strength of concrete, the modulus of elasticity is not affected by curing but influenced by the volume of aggregate and hydrate cement paste (Neville 1995). In studies on concrete mixes with pozzolanic materials such as silica fume and fly ash, higher modulus of elasticity at 28 days was obtained compared to the control (Iravani 1999). The author also found that at later ages, increase in modulus is less than that of compressive strength. Generally, the outcome of these pozzolanic materials on the modulus of elasticity is less than 3% on average.

3.4 Time dependent property

3.4.1 Drying shrinkage

Table 10 shows the drying shrinkage of selected high strength concrete specimens subjected to continuous air drying after demoulding or having initial 28 days water curing. At 1 year, mix NC10R1 recorded the highest

Table 6 Splitting strength / compressive strength ratio.

Mix No.	Splitting strength/compressive strength ratio (%)							
	Air Drying				Water Curing			
	7d	28d	180d	365d	7d	28d	180d	365d
WRNC2	6.3	6.3	6.0	5.9	6.4	6.2	5.7	5.8
WR10R2	4.8	5.9	6.0	6.2	4.5	6.1	5.8	5.8
WR10A2	5.5	5.8	5.7	5.9	5.7	6.1	5.8	6.0
NC10R1	5.1	6.0	5.8	6.0	5.4	6.3	6.1	6.1

Table 8 Flexural strength / compressive strength ratio.

Mix No.	Flexural Strength / Compressive Strength ratio (%)							
	Air Drying				Water Curing			
	7d	28d	180d	365d	7d	28d	180d	365d
WRNC2	12.9	10.6	10.0	9.8	13.6	11.1	10.1	9.9
WR10R2	12.8	10.9	11.1	10.9	13.5	10.9	10.0	9.9
WR10A2	13.3	10.9	10.7	10.6	13.4	11.0	10.3	10.2
NC10R1	11.8	10.7	10.2	10.1	12.0	11.0	10.3	10.2

Table 7 Flexural strength results for all HSC selected mixes up to 1 year.

Mix No.	Flexural Strength (N/mm ²)				Flexural Strength (N/mm ²)				Air drying Water curing Strength ratio		
	Air Drying				Water Curing				28d	180d	365d
	7d	28d	180d	365d	7d	28d	180d	365d			
WRNC2	6.30	6.45	6.63	6.65	6.78	6.82	6.90	6.91	0.95	0.96	0.96
WR10R2	6.41	6.82	7.01	7.05	6.85	7.01	7.10	7.15	0.97	0.99	0.99
WR10A2	6.72	7.09	7.13	7.16	7.08	7.37	7.48	7.53	0.96	0.95	0.95
NC10R1	6.92	7.20	7.28	7.30	7.20	7.58	7.60	7.65	0.95	0.96	0.95

Table 9 Static modulus of elasticity of four HSC mixes.

Mix No.	Static Modulus of Elasticity E_c (kN/mm ²)							
	Air Drying				Water Curing			
	7d	28d	180d	365d	7d	28d	180d	365d
WRNC2	20.9	23.4	24.5	25.4	24.0	25.6	30.2	30.9
WR10R2	21.1	24.8	28.1	29.0	22.1	26.1	31.3	32.1
WR10A2	24.3	26.2	30.2	31.4	24.0	29.5	34.2	34.9
NC10R1	24.8	27.5	31.5	33.0	25.8	30.7	36.5	37.5

Table 10 Drying shrinkage for selected high strength concrete mixes.

Mix No.	Shrinkage Strain (μ s)							
	Continuous Air Drying				Initial 28 Days Water Curing			
	WR NC2	WR 10R2	WR 10A2	NC10 R1	WR NC2	WR 10R2	WR 10A2	NC10 R1
w/b ratio	0.36	0.36	0.36	0.38	0.36	0.36	0.36	0.38
1d	35	40	41	58	20	15	35	43
3d	58	63	65	79	40	35	57	59
7d	76	78	83	98	44	49	63	68
14d	84	86	91	105	56	54	74	81
28d	98	98	110	123	68	70	82	96
56d	130	133	143	169	108	109	119	128
90d	142	145	151	171	110	135	146	153
120d	162	169	173	191	123	137	165	170
180d	173	173	184	203	152	152	170	183
365d	189	178	189	205	185	164	177	185

drying shrinkage amongst the four mixes, due to higher cement content. It is generally agreed that shrinkage increases with an increase in the cement content because this results in a large volume of hydrated cement paste which is liable to shrink (Neville 1995). Water reduced replacement mix WR10R2 exhibited the least shrinkage due to the least cement content. Addition of RHA to the water reduced concrete mix (Mix WR10A2) increase the drying shrinkage compared to the replacement mix WR10R2. Inclusion of RHA to water reduced concrete appears to help in reducing marginally the shrinkage of concrete. The measured shrinkage of RHA concrete at 1 year was between 164 to 190 microstrains, the result of which compared well with that of other investigators and types of concrete (Zhang and Malhotra 1996; Sugita *et al.* 1992; Swamy and Mahmud 1989).

3.5 Durability of RHA concrete

3.5.1 Water absorption test

Table 11 shows the results of the water absorption for

the selected HSC mixes, expressed in terms of percentage of dry concrete mass. The water absorption values for the water cured specimens displayed reduction of 6.8% - 14.9% and 12.9% - 23% at 28 days and 90 days respectively, compared to the corresponding air dried specimens. For water reduced concrete, irrespective of curing regime, WR10R2 mix exhibited the best resistance towards water absorption from 28 days onwards compared to that of WR10A2 and the control WRNC2 specimens. At 28 and 90 days, for both curing regimes, WR10R2 mix displayed reduced water absorption value of 14.5% and 10.26% respectively, compared to the control mix. The pozzolanic reaction of RHA reduced the ease of water absorbed into the concrete. This is because the dense masses of the hydration products decrease the pore volume (Khayat *et al.* 1997). These results show that irrespective of the method of inclusion and curing regime, incorporation of RHA lowers the water absorption value compared to that of the control mix without RHA. The high specific surface area of the RHA acts as a micro-filler, efficiently reducing the size of the capillary pores of the paste binder, causing the pore system to become segmented through partial blocking (Speare *et al.* 1999). In addition, the pozzolanic reaction of the RHA form secondary hydration products which filled up the voids, creating discontinuous pore network and effectively decrease the pore volume of the concrete.

Irrespective of the test age and curing condition, RHA 'addition' mix WR10A2 exhibited slightly higher absorption value than that of the 'replacement' mix WR10R2, but lower than the control mix WRNC2 mix was observed. In the 'addition' mix, the cement content was not replaced but the amount of sand and coarse aggregates were reduced. Therefore slightly higher porosity compared to the 'replacement' mix is expected. The normal RHA 'replacement' mix NC10R1 displayed higher absorption values compared to the water-reduced concrete mixes (WRNC2, WR10R2 and WR10A2). This is due to the higher w/b ratio of the former.

3.5.2 Sorptivity

Sorptivity measures the rate of capillary suction with no water head or pressure required. It characterized the tendency of a porous material to absorb and transmit water by capillary action (Hall 1989). The value of sorptivity illustrates the water mass uptake by concrete from the bottom surface, in unit of mm/min^{0.5}. The lower the

Table 11 Water absorption for selected HSC mixes.

Mix No.	w/b ratio	Water Absorption (%)				Reduction of water curing to air drying (%)		Reduction compared to WRNC2 mix, (%)	
		Air Drying		Water Curing					
		28d	90d	28d	90d	28d	90d	28d	90d
WRNC2	0.36	8.88	7.41	7.56	6.19	14.86	16.46	-	-
WR10R2	0.36	7.59	6.65	6.63	5.14	12.65	22.71	14.53	10.26
WR10A2	0.36	7.64	6.81	6.76	5.83	11.52	14.39	14.53	8.10
NC10R1	0.38	9.20	8.81	8.57	7.67	6.85	12.94	*-3.60	*-18.89

*-ve indicates greater water absorb than that of control WRNC2 mix.

Table 12 Sorptivity values for selected HSC mixes.

Mix No.	w/b ratio	Sorptivity ($\text{mm}/\text{min}^{0.5}$)			
		28 days		90 days	
		Air Dried	Water Cured	Air Dried	Water Cured
WRNC2	0.36	0.090	0.071	0.072	0.055
WR10R2	0.36	0.070	0.067	0.068	0.051
WR10A2	0.36	0.080	0.068	0.088	0.053
NC10R1	0.38	0.120	0.114	0.130	0.098

Fig. 2 Sorptivity value for selected HSC mixes.

sorptivity value, the higher is the resistance of the concrete towards absorption. **Table 12** and **Fig. 2** reveal that for water cured samples, the longer the immersion time, the lower is the sorptivity value due to the decrease in mass with time, compared to that to air cured specimens.

Generally, all mixes except for mix NC10R1 have sorptivity value lower than $0.1 \text{ mm}/\text{min}^{0.5}$. This is agreement with data by other researchers (Abdul Razak *et al.* 2004; Güneyisi and Mermedas 2007). For water reduced concrete under air drying, regardless of the method of inclusion (replacement or addition), presence of RHA results in slightly lower sorptivity values compared to the control WRNC2 concrete. Sorptivity values also decreased with age of concrete. Mix NC10R1 put forward the highest sorptivity value amongst the four mixes because this mix has the highest w/b ratio. This influence the characteristics performance of the concrete, making it less dense and less impermeable. For water cured samples, at the same w/b ratio, similar behaviour was observed, whereby the RHA mixes exhibited marginally lower absorption values than the control concrete. The pozzolanic reaction of the RHA concrete afforded pore refinement; reducing the number and size of large pores with finer pores, ultimately producing less interconnected network of capillary pores (Hall 1989). When compared to air dried specimens, specimens subjected to water curing generally exhibited marginally lower sorptivity values. Water curing is very important especially for mineral admixtures in influencing the durability characteristics of concrete.

The longer the period of water-curing, the higher is the resistance of RHA concrete towards absorption. Inclusion of mineral admixtures reduces the internal total

pore volume as well as redistribution of pore sizes in concrete (Swamy 1997). As for NC10R1 mix, results showed higher value of sorptivity compared to that of the water-reduced specimens. This is expected as the w/b ratio of this mix is higher. It can be observed from **Fig. 2** that the effect of curing method is more dominant in the mixes containing RHA since the values of the water cured specimens are much lower compared to the air-dried ones. For similar w/b ratio, the highest value exhibited by the control WRNC2 mix. This established the fact that inclusion of RHA is effective in producing impermeable concrete.

3.5.3 Resistance of concrete to sulphate ingress

Effect of immersion to magnesium sulphate solution and subsequent drying, on changes in length (expansion), weight and compressive strength of HSC mixes were investigated and discussed in the following sections.

(1) Expansion (length change)

Expansion data for all the concrete mixes are presented in **Table 13**. Results show that specimens subjected to initial 7 days water curing (7W) before immersion in sulphate solution exhibited lower expansion than that of air dried specimens. Irrespective of curing regime, the results show that the expansion value for RHA concrete mixes up to 3 cycles of exposure (111 days) was about 0.0165 % to 0.0263 %. In a report by the Canadian Standards Association (CSA), the two years maximum expansion criterion for concrete is about 0.04% (Shehata and Thomas, 2002). It can be noted that the expansion value for RHA concrete mixes, irrespective of the type of curing before exposure to MgSO_4 solution, is lower than the CSA criterion. For RHA concrete mixes subjected to 3 cycles of exposure, reduction in expansion compared to the control WRNC2 concrete for air-drying and 7W specimens were in the range of $2.0 \times 10^{-3} \%$ to $6.3 \times 10^{-3} \%$ and $0.7 \times 10^{-3} \%$ to $2.1 \times 10^{-3} \%$ respectively. Results also show that irrespective of curing regime, NC10R1 exhibited the largest reduction in expansion compared to WRNC2 concrete, but similar expansion to that of WR10R2 was observed. This result clearly indicated that RHA as a pozzolanic material plays a significant role in increasing deterioration resistance to magnesium sulphate solution. In addition, current finding also shows that inclusion of 10% RHA as cement replacement is more advantageous in reducing expansion compared to 10% RHA addition.

(2) Weight change

Data on the weight change for all concrete mixes subjected to 3 cycles of sulphate solution (3 % by weight of water) are presented in **Table 14**. Results show that specimens subjected to initial 7 days water curing (7W) before exposure to 3 cycles of magnesium sulphate solution exhibited lower weight change compared to air dried specimens. However, irrespective of curing regime,

Table 13 Expansion of HSC mixes subjected to exposure to 3 cycles of magnesium sulphate solution.

Mix No.	w/b ratio	Expansion (%) (x10 ⁻³)							
		Air-drying					Initial 7 days water curing (7W)		
		No. of cycles			Reduction compared to WRNC2 at Cycle 3	No. of cycles			Reduction compared to WRNC2 at Cycle 3
		1	2	3		1	2	3	
WRNC2	0.36	11.8	26.3	28.3	-	8.4	10.1	18.6	-
WR10R2	0.36	7.3	18.0	22.2	6.1	8.5	9.4	16.8	1.8
WR10A2	0.36	5.2	14.0	26.3	2.0	7.6	9.8	17.9	0.7
NC10R1	0.38	7.4	20.0	22.0	6.3	8.0	10.2	16.5	2.1

Table 14 Weight change for selected HSC mixes.

Mix No.	w/b ratio	Weight change (%) (x10 ⁻²)							
		Initial 7 days water curing (7W)				Air-drying			
		No. of cycles			Reduction compared to WRNC2 at Cycle 3	No. of cycles			Reduction compared to WRNC2 at Cycle 3
		1	2	3		1	2	3	
WRNC2	0.36	8	16	16	-	24	35	35	-
WR10R2	0.36	12	12	12	4	40	44	52	-17.0*
WR10A2	0.36	8	12	12	4	37	46	46	-11.0*
NC10R1	0.38	8	12	12	4	48	52	52	-17.0*

* -ve values indicate weight increase

the results show that the weight change value for RHA concrete mixes were 0.12 % reduction and 0.52 % increase for 7W and air dried specimens respectively. Up to 3 cycles of exposure, reduction in weight for RHA concrete mixes compared to the normal WRNC2 specimen, vary between -0.17 % to -0.11 % and 0.04 % for air drying and 7W specimens respectively. Results also show that all air dried RHA concrete produce increase in weight compared to WRNC2 concrete. This result indicates that RHA as a pozzolanic material has a significant effect in increasing resistance towards sulphate attack. Moreover, current experimental result shows that inclusion of 10% RHA as cement replacement gave similar reduction in expansion compared to the 10% RHA addition mix.

(3) Compressive strength

The compressive strength for selected concrete specimens subjected to exposure to 3 cycles of magnesium sulphate solution, as compared to the predicted strength of specimens subjected to water curing, is presented in **Table 15**. Data show that all mixes subjected to magnesium sulphate solution exhibit strength reduction ranging from 2% to 8%, irrespective of curing type. When specimens were subjected to 7 days initial water curing (7W), RHA concrete mixes produced higher strength compared to air drying. Under this curing method, 8% strength reduction was recorded for WRNC2 concrete at the end of 3 cycles of exposure (111 days). For RHA mixes, lower strength reductions were observed, i.e. 3% to 6%. It is also noted that NC10R1 is more resistant to magnesium sulphate solution compared to WR10A2 and

Table 15 Compressive strength after exposure to magnesium sulphate solution.

Mix No.	w/b ratio	Comp. strength* (N/mm ²) _{f_{ce}} No. of cycles			Comp. strength after exposure to MgSO ₄ solution (N/mm ²) _{f_{cs}} No. of cycles			Relative comp. strength at end of each cycle (f _{cs} /f _{ce}) No. of cycles		
		1	2	3	1	2	3	1	2	3
		37	74	111	37	74	111	37	74	111
Immersion to sulphate solution after demoulding at 1 day										
WRNC2	0.36	62.5	64.8	66.1	60.3	61.4	61.3	0.96	0.95	0.93
WR10R2	0.36	65.2	67.5	68.8	63.8	64.2	65.1	0.98	0.95	0.95
WR10A2	0.36	67.6	69.5	70.6	65.4	65.9	66.7	0.97	0.95	0.94
NC10R1	0.38	69.5	71.2	72.3	67.1	69.2	69.5	0.97	0.97	0.96
7 days initial water curing (7W) before immersion to sulphate solution										
WRNC2	0.36	62.5	64.8	66.1	60.8	61.2	60.7	0.97	0.94	0.92
WR10R2	0.36	65.2	67.5	68.8	64.1	65.8	65.4	0.98	0.97	0.95
WR10A2	0.36	67.6	69.5	70.6	65.4	65.8	66.2	0.97	0.95	0.94
NC10R1	0.38	69.5	71.2	72.3	65.9	66.3	69.8	0.95	0.93	0.97

WR10R2 mixes. Generally, RHA concrete needed some initial water curing to increase its resistance to magnesium sulphate solution.

4. Conclusions

The following conclusions can be drawn based on results of the current study: -

- (1) Irrespective of method of inclusion or percentage of RHA, workability of RHA concrete of 150 to 200 mm slump can be obtained using superplasticizer of less than 1.1% of the binder content.
- (2) Strength of 60 N/mm² can be achieved with the incorporation of RHA. The optimum 'addition' or 'replacement' level of RHA to produce optimum strength is 10%.
- (3) All RHA concretes were able to attain 70 N/mm² at 180 days onwards. Results also show that air-drying did not significantly affect the strength of RHA concrete mixes, i.e. average reduction of less than 6% was noted when compared to water cured samples.
- (4) Inclusion of RHA in a concrete mix appears to decrease the drying shrinkage compared to the control WRNC2 concrete. Irrespective of curing regime, 90% of the 365 days shrinkage occurred at six months.
- (5) Irrespective of the type of method of inclusion, at similar w/b ratios, RHA mixtures enhanced the durability of concrete by reducing its water absorption characteristics compared to control OPC concrete.
- (6) Irrespective of the method of inclusion, at similar w/b ratio, RHA concrete showed reduced values of sorptivity compared to the control OPC concrete. For air-dried specimens, RHA concrete shows slightly lower or similar values to that of the control concrete.
- (7) Irrespective of curing regime, when exposed to magnesium sulphate solution, expansion values of RHA concrete mixes are lower than the control OPC. After 3 cycles of exposure, all concrete mixes produce maximum expansion of less than 0.03%. This result clearly demonstrated the significant role that RHA performed in resisting deterioration to magnesium sulphate attack.
- (8) When subjected to magnesium sulphate solution, strength reduction of 6% was observed for the RHA concrete, whereas 8% reduction was noted for the control OPC concrete. This indicated that RHA is a beneficial component to resist magnesium sulphate attack in high strength concrete.
- (9) Based on the present study, it can be concluded that RHA is essential in the production of high strength grade 60 concrete. Its incorporation is beneficial in improving the durability of concrete.

Acknowledgement

The research described above is supported by an R&D grant 13-02-03-3007 (Development of high strength and durable rice husk ash concrete) under the 9th Malaysia Plan. The authors would like to thank the Ministry of Science and Environment of Malaysia for awarding the

grant. The help of BASF (Malaysia) and the National Rice Board of Malaysia for supplying the superplasticizer and rice husk are highly appreciated.

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