The Effect of Rice Husk Ash on the Strength and Durability of Concrete at High Replacement Ratio

Binyamien I. Rasoul[1,a], Friederike K. Gunzel[1,b], M. Imran Rafiq[1,c]

1– School of Environment & Technology, University of Brighton, UK

a – B.Rasoul@brighton.ac.uk

b– f.k.gunzel@brighton.ac.uk

c – M.Rafiq@brighton.ac.uk

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ABSTRACT. The objective of this study is to investigate the effects of Rice Husk Ash, with different replacement levels, on the strength and durability of concrete. Three types of rice husk ash with different chemical composition and physical properties were used for this study. Ordinary Portland Cement (OPC) type 52.5 N was replaced with 5%, 10%, 15%, 20%, 30%, 40% and 50% RHA (by weight) for strength test, additional samples with 60% RHA replacement were used for durability experiments. The ratio of water/cementitious material was kept at a constant value of 0.50. Superplasticizer was used to maintain a consistent workability of the fresh concrete. The compressive strength was measured after 7, 28 and 90 days, while splitting tensile strength was obtained at age of 28 and 90 days. The migration coefficient of chloride ion penetration was evaluated using non-steady-state migration tests [1] at 28 days age. The results revealed that the RHA properties (silica form, fineness, silica percentage and loss on ignition) have a direct impact on the development of strength at long-term age [2]. Experiments showed that even with 50% replacement of OPC with RHA, concrete has a higher strength and durability performance compared to OPC concrete. This may be attributed to the fact that increasing replacement ratios of RHA leads to a reduction in porosity, which in turn increases the strength and durability of concrete.

Introduction. Improving the concrete's performance by utilizing industrial and agricultural waste as supplementary cementitious materials is gaining popularity amongst researchers in recent years [3]. Pozzolanic materials such as fly ash, silica fume, ground granulated blast furnace slag and rice husk ash are by-products of other industries, containing high amounts of amorphous silica. This leads to a pozzolanic reaction the released calcium hydroxide of cement hydration process making these materials a suitable blending material for OPC. Rice husk ash is produce annually in huge quantities [4] by incinerating rice husk in electric power stations or by incinerating the husk at agricultural fields. The annual production of rice according to [5] in 2013 was 730.2 million tons. Rice husk is generally estimated about 20% of the plant weight and the ash is about 20% of the husk weight [6]. This huge amount of rice husk beside of environment dumping problem. Key ingredient of the RHA is reactive amorphous silica that reacts with calcium hydroxide liberated by cement hydration in concrete matrix to produce dense calcium silicate hydrates (CSH) that is mainly responsible for improved concrete performance [7].

Many studies investigated the effect of RHA blended cement in concrete mixtures; some include the effect of RHA on the strength and durability. However, there are many discrepancies in the results. For example, Mehta [6] found higher strength in concrete with up to 50% RHA compared to the OPC control, even as early as 3 days. Similarly, Isaia et al. [8] found that replacing cement by 50% RHA achieved the same strength as the OPC concrete.

On the other hand, many authors report only much lower replacement percentages as possible: Ganesan et al. [9] found that only up to 30% of OPC could be replaced with RHA without detrimental effects. Ettu et al. [10] report these as 15% RHA replacement without any reduction in strength. The optimum level of cement replacement with RHA was found to be between 10% and 20% according to Safiuddin [11]. Leong [12] reported that up to 5% of cement replacement by RHA increase the strength compare to OPC concrete. Madandoust et al. [13] and Marthong [14] show reduction in compressive strength for all RHA blended concrete compared to the OPC control. The positive effects of RHA on the concrete performance were attributed to the high content of amorphous silica and the very high surface area of the particles [8] and the particle characteristics such as shapes (spherical to un-regular ratio) [11].

Durability it is another important concrete property, which can be defined as the capability of concrete to resist weathering action and chemical attack. Many studies have investigated the impact of replacement of cement with RHA to enhance the performance of concrete [15]. However, the relationship between the physical and chemical properties of RHA to the level of replacement that can be used to reduce chloride ion penetration, is currently not fully understood. Madandoust et al. [13] concluded that blending Portland cement with RHA prevents the diffusion of Cl^-. The improvement is mainly caused by the reduction of permeability/diffusivity in blended concrete. As with the compressive strength, contradicting results are reported in the literature: some authors found that blending cement with up to 40% RHA increases corrosion resistance [16]. On the other hand, other authors reported a maximum of only 15% [18] to 25% [9], [17] of RHA to have a positive effect on the diffusion coefficient. The objectives of this study are to improve the understanding of the effects of the chemical and physical properties of the RHA on the concrete performance and to investigate the contradiction in literature data on the effect of RHA properties on the strength and chloride ion diffusion with the aim to find the optimum replacement ratio of cement by RHA depending on the properties of the RHA.

Research Programme.

A. Materials

1) Cement: The compositions of the cement (Rugby CEM I 52.5N) used in concrete blended RHA mixtures provided by the manufacturer (CEMEX UK Cement Ltd) is given in Table 1.

Table 1. Physical and Chemical Properties of OPC (CEM i 52.5n).

Physical properties									
Specific Surface area			450m^2/kg						
Initial setting time			130 minutes						
Chemical compounds (% of total cement mass)									
CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	SO_3	Na_2O	Cl^-	FL*	LOI
63.8	19.9	3.10	4.80	1.10	3.3	0.70	0.06	3.0	2.70
* FL = Free Lime									

2) Rice Husk Ash: Three different types of RHA were used as a partial replacement with cement. The rice husk ash was provided by Navdanya Food PVT LTD Odisha, India. X-ray fluorescence was used to determine the chemical composition, while the physical properties (particle size distribution and specific surface area) were obtained with a laser diffractometer Mastersizer 2000 particle size analyzer. The physical properties and chemical composition are given in Tables 2 and 3 respectively.

Table 2. Physical Properties of RHA Types.

RHA type	Specific surface area (m^2/kg)	Mean particle size (µm)	Reactive silica(% of total RHA weight)	Colour
RHA-A	537	23.397	69%	Grey
RHA-B	587	20.948	80%	Dark Grey
RHA-C	691	15.804	84%	Black

Table 3. Chemical Composition of RHA Types (% of Total Mass).

RHA type	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	SO_3	MnO	LOI*
RHA-A	92.10	1.07	0.24	0.72	-	-	1.37	0.40	0.08	0.11	3.80
RHA-B	89.31	1.39	0.39	0.99	-	-	1.81	0.75	1.10	0.17	5.10
RHA-C	84.30	1.07	0.18	0.73	-	-	1.52	0.68	0.08	0.14	11.35

*LOI: Loss on ignition of rice husk ash at 975±25°C for 15 minutes according to EN 196-2:1994

Table 4. Properties of Fine Aggregate (Sand).

Sieve aperture	Weight (g)	Percentage (%)	Cumulative passing (%)
4mm	11	2.2	97.8
2.8mm	43	8.6	89.2
1.4 mm	97	19.4	69.9
600µm	140	27.9	41.9
300µm	159	31.7	10.2
150µm	45	9.0	1.2
75µm	4.0	0.8	0.4
63µm	1.0	0.2	0.2
Pan	-	-	-

Table 5. Properties of Coarse Aggregate (Gravel).

Sieve aperture	Weight (g)	Percentage (%)	Cumulative passing (%)
9.5 mm	15	3.0	97.1
8.0 mm	48	9.6	87.5
4.0 mm	341	68.1	19.4
Pan	97	19.4	-

3) Fine Aggregate: The sieve analysis of fine aggregate (sand) according to British Standard BS EN 12620 [19] is presented in Table 4.

4) Coarse Aggregate: Uncrushed gravel (maximum size 10 mm) was used as coarse aggregate according to the British Standard BS EN 12620 [19]. The sieve analysis of aggregates is presented in Table 5.

5) Superplasticizer: Fosroc Auracast 200 superplasticizer was used in the experimental work. According to the manufacturer, the Fosroc Auracast 200 has a high range water reducing capabilities and excellent scattering levels with strong performance. The main objective of using superplasticizer is to increase the workability of concrete blended RHA in order to require little vibration during casting.

B. Experimental Procedure

1) Strength of Concrete: The mix design for concrete was based on British mix design method (DOE) [20]. The target mean strength was 50 MPa for the OPC control mixture at 28 days. Details of the mix proportion of the concrete mixes are presented in Table 6. The water to binder ratio (w/b) kept constant at 0.50 as well as the portion of fine aggregate (785 kg/m^3) and coarse aggregate (800 kg/m^3); superplasticizer was used to keep the workability to a slump of 50-200 mm. The total time of mixing was 5 minutes. Standard 100 mm cubes were cast from each mixture to measure the effect of RHA on the compressive strength at the age of 7, 28, and 90 days. All specimens were kept in the molds for 24 hours and then placed in water for curing until the day of testing. The splitting tensile strength was measured at 28 and 90 days using 100mm diameter and 200mm high cylinders.

Table 5. Concrete Mix Proportions.

RHA Replacement (%)	Cement (kg/m^3)	RHA (kg/m^3)	Superplasticizer (%)
0	460	0	0.25
5	437	23	0.25
10	414	46	0.25
15	391	69	0.25
20	368	92	0.25
30	322	138	0.50
40	276	148	1.00
50	230	230	2.00

2) Chloride Ion Penetration: Chloride ion penetration was measured by the Nordtest (NT BUILD 492) method [21], which is a non-steady state migration method based on a theoretical relation between diffusion and migration. The method enables the calculation of the apparent chloride diffusion coefficient (D_{nssm}) from an accelerated test [1]. The samples were prepared from 28 day cured cylinder specimens sized 100mm diameter and 200mm height; these are cut with a saw to 50 mm high cylindrical slices. After the specimen was placed on the plastic support in the catholyte reservoir (10% NaCl solution) the sleeve above the specimen with was filled with 300 ml of 0.3N NaOH as anolyte solution (see Figure 1). A 30V electrical potential was applied and the initial current through each specimen was recorded. Then, after adjusting the voltage depending on the value of the initial current the test was continued for 24 to 96 hours depending on the initial current.

The principle of the test is that chloride ions are forced to migrate out of the 10% NaCl catholyte solution subjected to a negative charge at the surface of the specimen, through the concrete into the 0.3N NaOH anolyte solution at the opposite surface of the specimen. After the test, the specimen is axially split and a silver nitrate solution is sprayed on to one of the freshly split surfaces; the chloride penetration depth (x_d) is measured by observation of the color change in order to calculate the apparent non steady state diffusion migration coefficient (D_{nssm}). Figure 1 shows the details of the test setup.

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{U-2}}\right) \quad (1)$$

where D_{nssm} – is the non-steady-state migration coefficient ($\times 10^{-12}$ m^2/s);

U –is the absolute value of the applied voltage (V);

T – is the average value of the initial and final temperature in the anodic solution (ºC);

L – is the thickness of the specimen, usually 50 mm;

x_d – is the average value of measured chloride penetration depth (mm);

t – is the testing period (h).

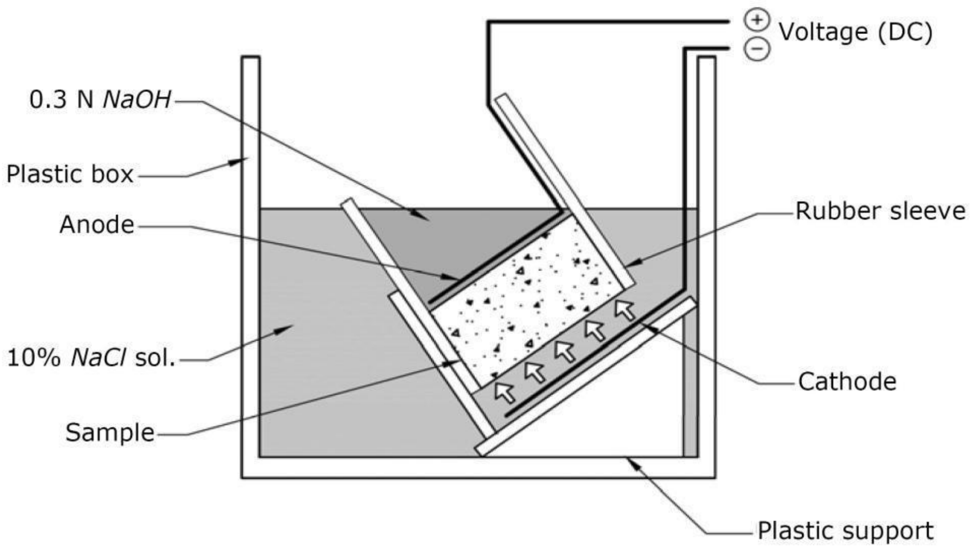

Fig. 1. The non-steady state migration test set-up: Anolyte (0.3M NaOH), Catholyte (10% NaCl) [1].

Results and Discussion. The results of the compressive strength tests to determine the optimum RHA replacement in concrete are shown in Figure 2; each data point represents the average value of three samples. The RHA blending increases the strength at the early age (7 days) up to 15% replacement ratio, for all RHA types. This early strength increase is unexpected as reactive silica cannot provide significant strength contribution unless hydration is at a progressed state (e.g. [18]). The early strength development may be attributed to the filler effect (physical) of the fine-grained RHA rather than the pozzolanic effect (chemical).

However, the strength increase is most pronounced at the age of 28 days as a result of RHA silica reacting with the calcium hydroxide of cement hydration. This means that in RHA blended concrete, the $Ca(OH)_2$ formed during hydration of Portland cement is rapidly consumed due to the high pozzolanic reactivity of RHA. As time passes the rate of hydration reaction is faster than OPC and thus producing more secondary CSH. The volumes of $Ca(OH)_2$ crystal are reduced and higher volume of CSH than OPC are seen and consequently accelerates and enhances the hydration [22].

A. Compressive Strength

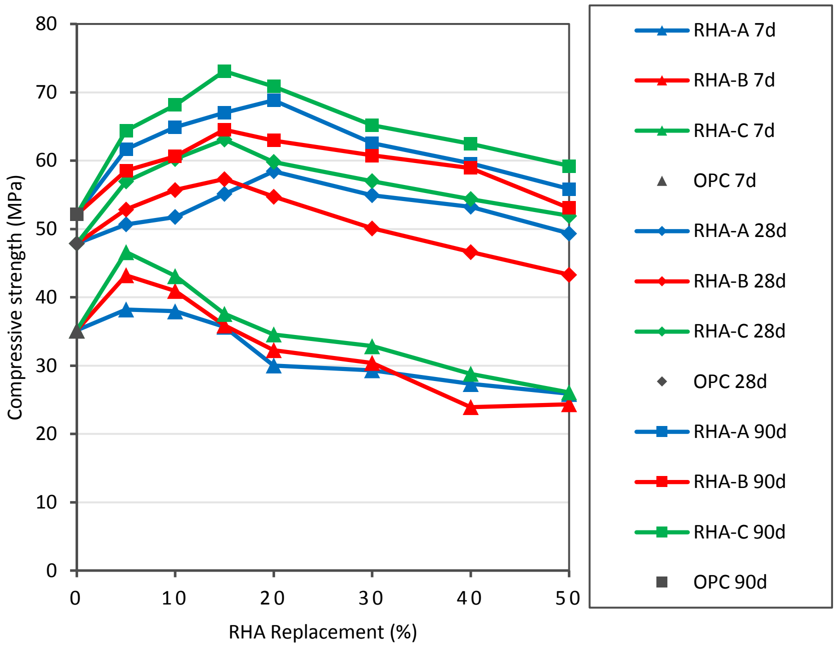

Fig. 2. Compressive strength of control and RHA blended concrete.

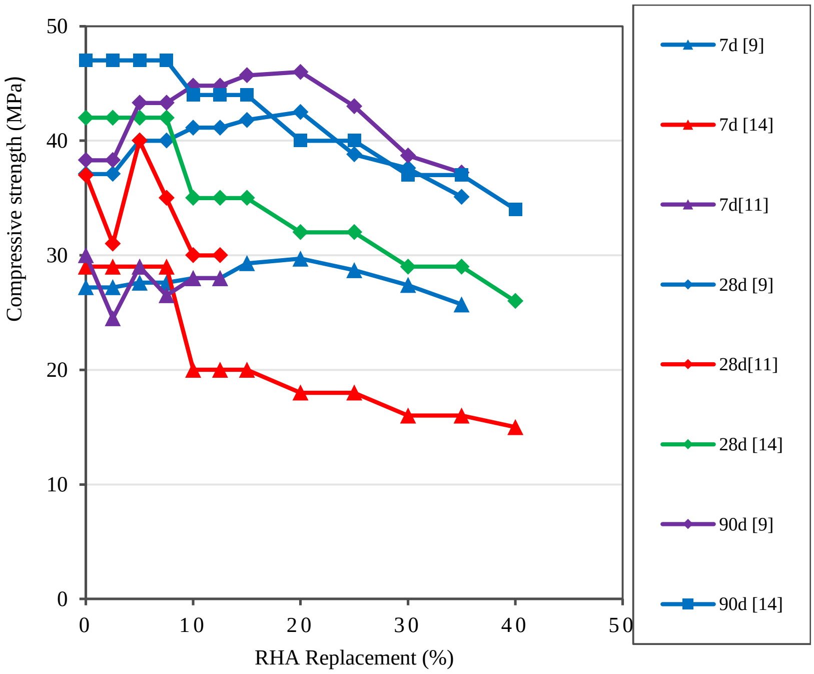

Fig. 3. Compressive strength of RHA blended concrete from [9] [10] [13] [14].

Moreover, the high amount of amorphous RHA silica (RHA-C) consisting of irregular or angular and spherical shaped particles [1], [23], [24] with high fineness of particles improve the particle packing density of the blended cement, leading to a reduced volume of larger pores and a more homogenous microstructure of the cement paste, particularly in the interfacial zone around the aggregate leading to increase the strength. Based on the RHA properties given in Tables 1 and 2 (amorphous silica structure and high surface area) RHA-C blended concrete shows in the highest increase of the compressive strength with increasing replacement ratio up to 15%; the compressive strength increased about 29% compared to the control sample. However, the strength of RHA concrete declines with increasing replacement ratio over 15%; nevertheless, even with 50% replacement the compressive strength of RHA-C (84% amorphous silica) concrete was still 12% higher than the control sample. This result confirms the result obtained by Mehta [6] and Isaia et al., [8]. This phenomenon can be explained by the amorphous siliceous nature and very high fineness that make RHA-C a highly reactive pozzolana. On the other hand, the performance of RHA with partially crystalline silica (RHA-A 25% crystalline; RHA-B 10% crystalline) exhibit higher compressive strength at 50% replacement after 90 days about 6.69% and 1.77% respectively compared to OPC concrete due to the crystalline silica particles behavior as a micro filler justifying better the density of mixture.

Comparing the experimental results to the published literature ([8], [9], [10], [11], [13], [14]) it can be seen from Figure 3 hat the results are very inconsistent: the compressive strength increases with RHA content up to 30% [9], while the results from [10] and [13] show compressive strength reduction for RHA blended concrete.

Furthermore, the value of compressive strength decreases below that of OPC concrete beyond 35% RHA mixture [9]. Similar results were reported by Zhang and Malhotra [7], where 30% is the optimal limit of replacement without negative impact on the strength of concrete. Moreover, Karim et al. [25] concluded after doing a review on the literature of RHA impact on the strength of mortar and concrete that 30% replacement ratio appears to be the optimal limit. On the other hand, the results obtained by Isaia et al., [8] showing excellent performance of concrete blended RHA even with 50% replacement ratio compared to the OPC concrete. This high performance of concrete blended RHA was due to the amorphous silica structure and the finesses of RHA particle size according to Ganesan et al. [9].

B. Splitting tensile strength

The results of the splitting tensile strength at 28 and 90 days are presented in Figure 4. From the observation, the splitting tensile strength at long-term age is higher than the control for all RHA replacement percentages. The increase of splitting tensile strength at 50% RHA replacement is 11.17%, 9.14% and 15.17% for RHA-A, B and C respectively. However, the results from the literature are again inconsistent: Several authors ([26], [26], [26]) report a reduction of splitting tensile strength with increasing RHA content for RHA contents up to 20%. This has been explained by the increased brittleness of RHA concrete [29]. On the other hand, several authors ([29], [23]) reported an increase of splitting tensile strength for maximum RHA replacements up to 25%.

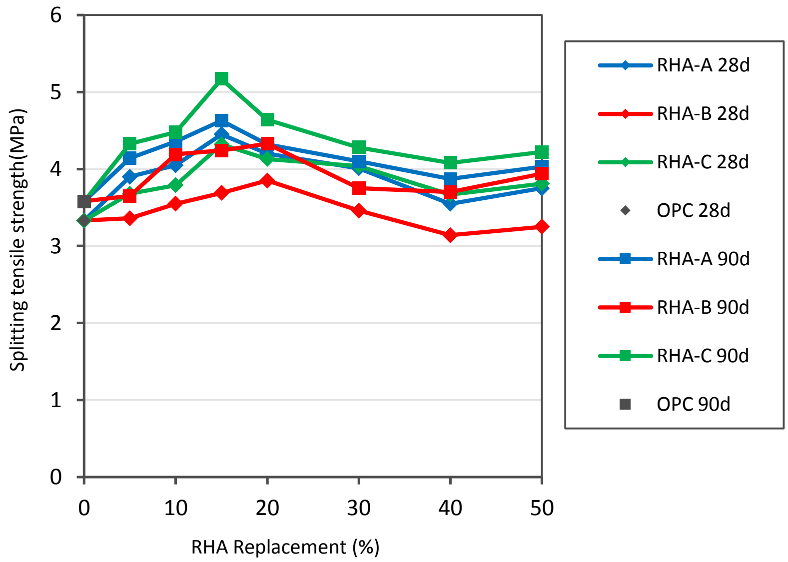

Fig. 4. Splitting tensile strength of control and RHA blended concrete.

C. Chloride Permeability

The results of the non-steady state migration test are illustrated in Figure 4. The results show that using RHA drastically enhances resistance to chloride ion penetration compared to the control concrete. Resistance to chloride ion penetration in concrete was improved from 11.55×10^{-12} m^2/s to 1.77×10^{-12} m^2/s, 2.19×10^{-12} m^2/s and 0.80×10^{-12} m/s^2 for 50% replacement with RHA-A, B and C respectively. The improved resistance for chloride penetration was also reported by several other authors ([9], [17], [18], [31], [32]); the optimum replacement in these studies was reported to be between 15% and 25% [9].

With increased RHA replacement up to 60%, the chloride penetration of RHA-A concrete reduced further to 2.10×10^{-12} m^2/s, while RHA-B and C showed an increase to 1.64×10^{-12} m^2/s and 0.98×10^{-12} m^2/s respectively. The behavior of RHA-A can be attributed to two factors; first, the high amount of silica content (92.10% of total weight), of which about 75% are amorphous. Second, the behavior of crystalline silica (about 25% of silica) as micro filler after all amorphous silica reacted with calcium hydroxide of cement hydration. It can be seen that the diffusion coefficient of RHA blended concrete specimens continuously decreases with increase in RHA content up to 50% of RHA-C and B, while continues decreasing with RHA-A even with 60%; nevertheless, still higher than RHA-C coefficient at 60% replacement ratio.

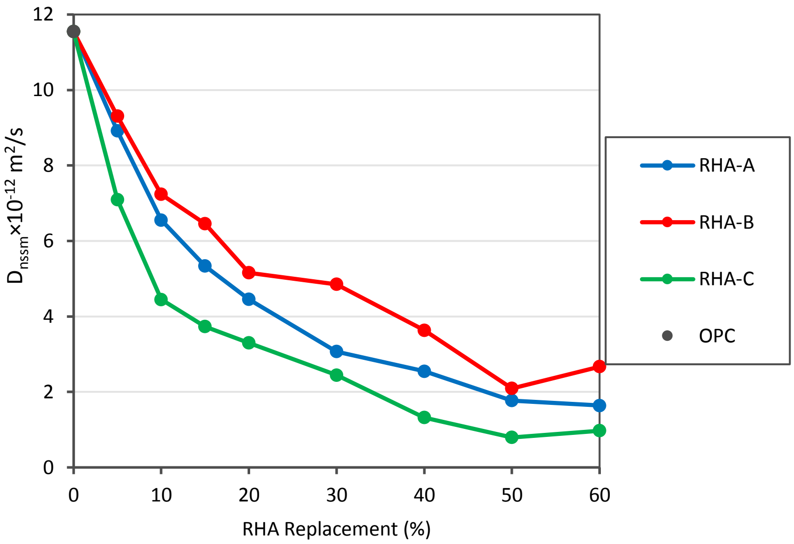

Fig. 5. Chloride ion diffusion of RHA concrete after 28 days.

D. Effect of Superplasticizer Ratio on Strength

Results of cubes and cylinders with superplasticizer obtained from experimental analysis shows that by using superplasticiser in RHA concrete the compressive and tensile splitting strength of concrete were increased. Several authors report increase of strength and durability for concrete with superplasticizer compared to control samples ([33] [34] [35]). The strength increase may be as large as 30% at 7 days and 50% at 28 days when the author used superplasticizer 1.61% of cement weight [32]. The positive effect has been attributed to improved compaction of concrete and more water being available to lubricate the mix [38].

Summary. The results presented in this paper indicate that up to 50 % of rice husk ash (by weight) can be incorporated in concrete without adversely affecting on the strength and durability of the concrete. Based on experimental results, the following conclusions can be drawn:

1. The obtained test results showed that the compressive and splitting tensile strength of concrete have noticeably been improved. These properties are influenced by variations in reactive silica content in the RHA (the higher the amount of silica in amorphous form, the higher the concrete strength and resistivity value became), amount of crystalline to amorphous silica form content, grain size of RHA particles, concrete age, Best results were achieved with the more reactive RHA (RHA-C). The coarser, less reactive RHA-A and B produced lower strength results for the whole range of cement replacement.

2. The increase in compressive and tensile strength of concrete with RHA containing a high amount of crystalline silica (RHA-A and B) is better justified by the filler effect (physical) than by the pozzolanic effect (chemical). After depletion of all amorphous silica by reacting with calcium hydroxide [$Ca(OH)_2$] to produce secondary C-S-H gel, the remaining silica, which is in crystalline form will behaves as a filler.

3. According to the experimental results as much as 60% by weight of OPC can be replaced by all RHA types used in the study improving the durability of concrete (chloride ion resistance); the best results were achieved with RHA-C with a 91% reduction of chloride penetration; this can be attributed to the high reactivity of the amorphous silica and fine grain size of RHA-C. This is a much higher reduction than previously reported in the literature where only a 15% to 40% reduction could be achieved ([16], [18]).

4. Overall RHA-C performed best of all three RHA types used in this study. Both compressive and tensile strength had a maximum at 15% replacement, but were still higher than the control concrete at 50% replacement. The reduction of chloride penetration was at a maximum at 50% replacement with only a slight reduction at 60% replacement.

5. The many discrepancies in published literature on strength and durability of RHA blended concrete can be attributed to the different RHA properties used by various authors. Especially the content of active (amorphous) silica and the grain size have a large influence on its performance as pozzolanic material.

Based on the results of the present study the future work will investigate the following points:

– Investigations will be undertaken to determine the effect of increasing the RHA content (for up to 70% or more) on the properties of concrete, and investigate the effect of high dosage of superplasticizer on the workability and compressive and splitting tensile strength.

– RHA with defined properties will be produced by controlled re-incineration and grinding; this will be used to further investigate the effect of RHA particle grain size and the content of amorphous silica on the strength and durability of the concrete.

– Experiments will be carried out using different amounts of superplasticizer to be able to distinguish between the effect of the superplasticizer and RHA on the strength and durability of the concrete.

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