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Application of Industrial Waste in Manufacturing of Self Compacting Concrete

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Highlights

The purpose focused on the behaviour of the red mud in SCC.
The red mud has good pozzolanic activity.
The red mud significantly reduces the segregation and bleeding of SCC.
The compressive and tensile splitting strength are enhanced.
The red mud incorporation in SCC reduces the drying shrinkage.

Abstract: Red mud derived from alumina refineries through the Bayer process is a waste material with a density of 2187 kg/m^3. The particle size distribution of the red mud is similar to fly ash. In this paper, the physical and chemical properties of the red mud including oxide and mineral contents are studied. The potential use of the red mud as a pozzolanic material to replace fly ash in self-compacting concrete (SCC) is assessed by conducting a range of fresh and hardened properties test (such as slump flow, density, porosity, compressive strength, splitting tensile strength, elasticity modulus and drying shrinkage). The XRF and XRD results show that the oxide forms in the red mud are mainly SiO_2, Al_2O_3 and CaO at 45.76%, 40.69% and 4.98% respectively, and the crystalline phases are mainly gismondine, goosecrekite and epistilbite which belong to the zeolite family. The results show that the strength activity indeces (SAI) of the red mud are 79.60 and 88.46 at 7 days and 28 days respectively, which are approximately equal to that of a common Class F fly ash. Meanwhile, with the use of the red mud to replace fly ash in SCC, the compressive strength, splitting tensile strength and elasticity modulus are enhanced. Moreover, with the addition of the red mud, the drying shrinkage decrement is observed in SCC, which might be due to the red mud's internal curing. Therefore, the feasibility of utilizing the Bayer red mud in SCC is demonstrated.

Keywords Red mud Self-compacting concrete Reutilization

I. INTRODUCTION

In recent years, some researches are focused on the reutilization of industrial waste residues (e.g., waste glass, concrete waste) in concrete or mortar to improve some properties (Guo et al., 2015, Zhao et al., 2013, Oliveira et al., 2015, Kou et al., 2012, Torres-Carrasco and Puertas, 2015). Bauxite contains large amounts of aluminium hydroxides and is therefore largely used for the production of alumina (Al_2O_3) through the Bayer chemical process, which is based on the reaction with sodium hydroxide under heat and high pressure (Brunori et al., 2005). But the by-product of the Bayer process is the generation of a large quantity of solid waste called “red mud” (the production of 1 t of alumina generally results in the generation of about 1–1.5 t of red mud).

Red mud generally has a high alkalinity, so its disposal can cause serious environmental problems. Huge areas of land are required for building red mud dam which are used for the storage of red mud. When disposed on land, the alkaline solution and red mud slurry may leach into ground or underground water (Yang et al., 2006). Therefore, there have been many interests devoted to the study of the reutilization of red mud. Many researchers extract precious metals from red mud, use red mud in polymer composite (Liu et al., 2009, Park and Jun, 2005), and reuse the waste to produce ceramic, cement or bricks (Smirnov and Molchanova, 1997, Ochsenkuhn-Petropoulou et al., 2002, Zhang et al., 2005, Tsakiridis et al., 2004, Pontikes et al., 2007, Yang et al., 2006, Ribeiro et al., 2012). For example, Pontikes et al. (2007) carried out some research works in producing ceramic with Bayer red mud, which has the potential of utilization red mud in industries; Yang at al. used red mud from Shandong Aluminium Plant to produce unsintered brick, which may have a huge application in the market of construction materials. However, interests might be seldom focused on the study of effects of red mud on the mechanical properties of concrete. Ribeiro at al. used red mud to improve the corrosion resistance of concrete. Their results show that the higher the red mud content the lower the corrosion rate, which stabilizes between 20 wt.% and 30 wt.% of added red mud content.

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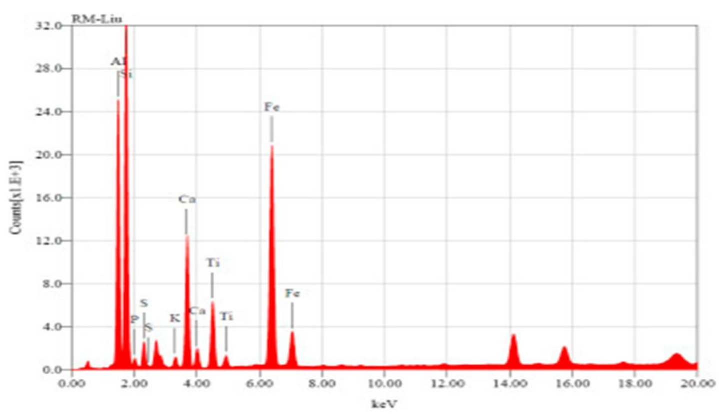
In this paper, the authors added the red mud in self-compacting concrete (SCC) to assess its effects on mechanical properties of SCC. Conventionally, self-compacting concrete is produced with the use of a high powder (fine material) content to ensure the freshly prepared concrete would not suffer from segregation. The powder is normally comprised of fly ash or limestone powder. In this study, the red mud is directly incorporated in SCC as a replacement of fly ash. In addition, the red mud used in this paper is composed of large amount of zeolite-type materials; hence, the effects of zeolite on properties of concrete are valuable and helpful for assessing the behaviors of the SCC incorporated with the red mud.

In recent years, many studies on the use of zeolite in cement or concrete have been reported (Colella et al., 2007, Feng and Peng, 2005, Hauri, 2006, Poon et al., 1999, Chan and Ji, 1999, Feng et al., 2002, Janotka et al., 2003). Zeolite, a hydrated aluminosilicate of alkali and alkaline earth metals is a common type of natural pozzolan for use in cement and concrete (Colella et al., 2007, Feng and Peng, 2005, Hauri, 2006). This material has been applied in the production of paving stones, concrete slabs, ready mixed concrete, and high-strength concrete pipes.

Simultaneously with the growing trend of applying natural zeolite in the cement and concrete industry, several research studies have been conducted to study its effects on concrete properties and compare this natural pozzolan with other pozzolanic materials (Poon et al., 1999, Chan and Ji, 1999). Poon et al. (1999) found that the pozzolanic activity of natural zeolite is higher than fly ash and lower than silica fume. Chan and Ji (1999) also compared the effectiveness of zeolite in enhancing the performance of concrete in comparison with silica fume and pulverized fuel ash (PFA). They conclude that zeolite is more effective than PFA in improving the compressive strength and decreasing the initial surface absorption and chloride diffusion but it is less beneficial than silica fume.

In a few recent studies, zeolite aggregates have indeed been utilized as internal curing agents (Feng et al., 2002, Janotka et al., 2003). Bilek et al. (2002) treated a fine zeolite powder (clinoptilolite) with density 2300 kg/m^3 by soaking in water for 7 days and then added to high-performance concrete with low w/c. Concrete mixtures with 10% zeolite show a small decrease in the elastic modulus and a similarly limited decrease in the autogenous shrinkage. In addition, in Zaichenko (2011), a fine zeolite aggregate (0.63–5 mm) from Ukraine (of unspecified type but composition compatible with clinoptilolite) is added to high-performance concrete mixtures. While the water absorption is 33% by mass, no characterization of the pore structure of the zeolite was reported. Zeolite aggregate reduced the autogenous shrinkage of the concrete; however, a pronounced shrinkage upon drying, higher than for the reference concrete, was observed.

Based on the previous researches, zeolites possess proper pozzolanic activity and their use as partial replacement of Portland cement lead to durability enhancement of cement and concrete composites. Simultaneously, in the view of reducing the autogenous shrinkage of concrete, zeolite may have an effect of internal curing. In this study, the main purposes are to explore if the red mud in SCC possess pozzolanic activity and internal curing effects and, in addition, investigate its effects on other mechanical properties of SCC.



II. EXPERIMENTAL DETAIL

A. Materials

The red mud with a density of 2187 kg/m^3 used in this study was a by-product of the refining of bauxite into alumina in an alumina plant in Shanxi Province, China. The chemical and mineral compositions of the red mud are analyzed by XRF and XRD. The results of the chemical analysis of the red mud are shown in Fig. 1 and Table 1. Based on the XRD analysis shown in Fig. 2, gismondine, goosecrekite and epistilbite were found in the red mud.

The three mineral compounds, with a three-dimensional structure made up by Si–O tetrahedroids and Al–O tetrahedroids, belong to the zeolite group, which has been demonstrated to be able to enhance the properties of concrete according to previous studies (Poon et al., 1999, Feng and Peng, 2005, Janotka et al., 2003, Ahmadi and Shekarchi, 2010, Ahmadi, 2007; Shekarchi et al., 2008, Najimi, 2010, Bilim, 2011). The particle size distribution (in Table 2) of the red mud was determined in accordance with BS 3892-1 (1997), and the percentage passing the 0.045 mm sieve was 76%.

Fig. 1. Oxide forms of the red mud by XRF.

Table 1. Chemical composition of the red mud and fly ash used in this experiment.

Material	SiO_2 (%)	Fe_2O_3 (%)	Al_2O_3 (%)	TiO_2 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	P_2O_5 (%)	LOI (%)
Fly ash	47.62	7.35	27.4	1.23	8.11	3.55	0.57	0.88	0.87	–	3.90
Red mud	45.76	2.85	40.69	2.03	4.98	0	2.15	0.45	0	1.10	–

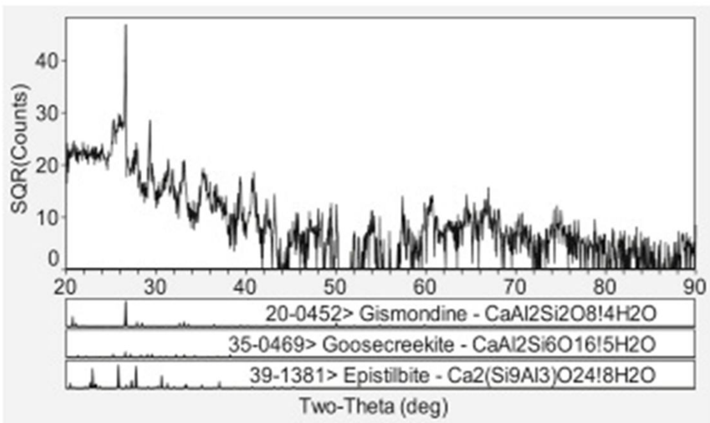


Fig. 2. XRD pattern of the red mud

Table 2. Particle size distribution of red mud and fly ash.

Size of BS test sieve (mm)	Percentage passing (wt.%)	
	Red mud	Fly ash
0.6	100	100
0.3	98.5	100
0.15	96.5	99.0
0.075	86.0	97.9
0.045	76.0	96.0

Ordinary Portland cement and fly ash were used as the cementitious materials in the reference (control) SCC mixtures. Type I Portland cement, corresponding to a specific area of 3520 cm^2/g and a density of 3150 kg/m^3, was used. The fly ash in this study was a by-product obtained from a coal-fired power plant in Hong Kong. The chemical and physical properties of the fly ash used in out tests are given in Table 1, Table 2

A crushed granite was used as the coarse aggregates and it had a specific gravity of 2650 kg/m^3, a 24-h water absorption of 1.12% and a maximum size of 10 mm. River sand with a nominal maximum size of 5 mm and a specific gravity of 2620 kg/m^3 was used as the fine aggregates. The corresponding physical and mechanical properties of the aggregates were shown in Table 3.

In this study, the super plasticizer used was a chemical admixture (Grace, ADVA-109) commercially available in Hong Kong.

B. Concrete Mixture Proportions

In order to compare the pozzolanic activity of the red mud with fly ash in mortar mixtures, three different mix proportions were designed in accordance with ASTM: C311-11b (2011) (listed in Table 4). In the sample test mixtures (FA-Mix and RM-Mix), 20% of the mass of cement used in the reference sample mixture named "control-I" was replaced by fly ash (FA) and the red mud (RM) respectively. The water requirements of FA-Mix and RM-Mix were adjusted to meet the flow of the "control-I" mixture with a tolerance of ±5 mm.

Table 3. Properties of coarse aggregates and river sand.

Material	Maximum size (mm)	Density (kg/m^3)	Water absorption (%)	
			10min	24h
River sand	5	2620	0.36	0.88
Coarse aggregate	10	2650	0.67	1.12

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Concrete Mixture Proportions

Table 4. Mix proportion of control- I, FA-Mix and RM-Mix mixtures.

Mix code	Cement (g)	Fly ash (g)	Red mud (g)	Sand (g)	Water requirement (g)
Control-I	500	0	0	1375	242
FA-Mix	400	100	0	1375	242
RM-Mix	400	0	100	1375	252

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In order to investigate the effects of using red mud to replace fly ash on the workability and mechanical properties of SCC mixtures, some SCC sample mixtures having different mass proportions between red mud and fly ash, according to Table 5, were designed. In this investigations, the reference sample, named "control-II", consisted of cement, fly ash, sand and coarse aggregate. The red mud was used to replace fly ash at 10%, 20%, 30% and 40% by weight correspondingly in SCC-RM10, SCC-RM20, SCC-RM30 and SCC-RM40 samples, respectively.

Table5. Mix proportion of SCC mixtures.

Mix code	Cement (kg/m^3)	Fly ash (kg/m^3)	Red mud (kg/m^3)	Ratio of replacement (%)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	w/c	Water (kg/m^3)	SP (L/m
Control-II	359	311	0	0	635	872	0.50	178	5.6
SCC-RM10	359	279.9	31.1	10	635	872	0.50	178	6.2
SCC-RM20	359	248.8	62.2	20	635	872	0.50	178	6.6
SCC-RM30	359	217.7	93.4	30	635	872	0.50	178	7.2
SCC-RM40	359	186.6	124.6	40	635	872	0.50	178	8.2

C. *Casting and curing of samples*

For the pozzolanic activity tests, all the mortar samples were cast into 70.7 × 70.7 × 70.7 mm cubes for the determination of compressive strength at 7 and 28 days. After casting, all the samples were placed in the laboratory environment at 23.0 ± 2.0 °C for 24 h. After that, the molds were removed and the mortar specimens were stored in saturated lime water as specified in ASTM: C109/C109M (2008) until the time of testing.

For the SCC mixtures, a variety of tests were conducted before the concrete casting to determine their fresh properties including the slump flow, J-ring, L-box and segregation resistance tests. For each SCC mixture, twelve 100 × 100 × 100 mm cubes were cast for the determination of compressive strength, twelve 100 × 200 mm cylinders were cast for the determination of splitting tensile strength and elastic modulus. Furthermore, three 70 × 70 × 285 mm prisms were cast for measuring the drying shrinkage. After casting, all the samples are covered with plastic sheets for 24 h and then demoulded. Then all the concrete samples were transferred to a standard water curing tank at 27 °C until the time of testing.

D. *Test Methods*

1) *Pozzolanic Activity*

According to the ASTM: C311-11b (2011), the strength activity index (SAI) was used to evaluate the pozzolanic activity of the red mud and fly ash. The compressive strength, of three samples of the control mixture and three samples of the test mixture at ages of 7 and 28 days, was determined. The strength activity index was calculated by the formula:

SAI= (A/B)X100

Where,

- *A* is average compressive strength of test mixture cubes, MPa, and,
- *B* is average compressive strength of control mix cubes, MPa.

2) Workability of SCC mixtures

The slump flow and t_{500} time were used to assess the flowability and the flow rate of the SCC in the absence of obstructions in accordance with BS EN 12350-8 (2010). The results were the indication of the filling ability of the SCC. The slump flow values were represented by the mean diameter (measured in two perpendicular directions) of concrete after lifting the standard slump cone (shown in Fig. 3a), given by the following equation:d

d=(d1+d2)/2

where,

- d_1 is the largest diameter of flow spread, mm, and
- d_2 is the flow spread at 90° to d_1, mm.

The t_{500}, which was used to measure the flow speed of the SCC, was the time taken to reach 500 mm of flow.

The J-ring test was used to determine the passing ability of the concrete as specified in BS EN 12350-12 (2010). It was an extension of the slump flow test in which a ring apparatus was used and the average diameter outside of the ring was measured to evaluate the passing ability of the SCC mixtures (Fig. 3b).

The L-box test was performed in accordance with BS EN 12350-10 (2010). This test was used to assess the flowability and passing ability of concrete. During the test, SCC mixtures was allowed to flow upon the release of a trap door from the vertical section to the horizontal section via a few reinforcement bars of a L-shape box. The height of the concrete at the end of the horizontal section was compared to the height of concrete remaining in the vertical section (shown in Fig. 3c).

3) Hardened Density and Water Porosity

The hardened density and the water porosity of the SCC mixture samples were determined by using a water displacement method according to BS EN 12390-7 (2009). The results of the average of three samples were reported.

4) Compressive strength and tensile splitting strength

The 100 mm SCC cubes and cylinders with 100 mm (diameter) by 200 mm (height) were used for the determination of the compressive and tensile splitting strength, respectively at 7, 28, 56 and 90 days according to BS 1881-116 (1983) and BS 1881-117 (1983). The compression load was applied using a compression machine with 3000 kN capacity, at the rate of 200 kN/min and 57 kN/min for the compressive and the tensile splitting strength test, respectively.

5) Elastic modulus

The static modulus of elasticity of SCC mixtures was determined in accordance with ASTM C469/C469M (2010). In this experiment, the tests were carried out on all samples at 28 days.

6) Drying shrinkage

A modified British Method (BS ISO1920-8, 2009) was used and 70 × 70 × 285 mm SCC mixture samples were prepared for the drying shrinkage test. After removing the samples from the curing tank after 7 day of curing, the initial length of each sample was measured. After the initial reading, the samples were conveyed to a drying room with a temperature of (22 ± 2) ^{o}C and a relative humidity of (55 ± 5) % until further measurements at 1, 4, 7, 28, 56, 90 and 112 days after the initial measurement. All drying and measurement of samples was carried out in the drying room, with the temperature and relative humidity within the range specified above.

III. RESULTS AND DISCUSSION

A. Pozzolanic Activity of the Red Mud

The SAI of the red mud and fly ash are presented in Table 6. The results show that the SAI of the red mud are 76.60% and 88.46% at 7 days and 28 days respectively, which are roughly equivalent to those of fly ash. This might be due to the fact that the red mud contained many active components which presented the pozzolanic activity; meanwhile, the effects of internal curing of the mineral compounds (belonging to zeolite) in the red mud enhanced the compressive strength of RM-Mix samples.

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Table 6. The SAI of red mud and fly ash.

Mix code	Average value of compressive strength (MPa)		SAI (%)	
	7 days	28 days	7 days	28 days
Control-I	32.963	42.729	–	–
FA-Mix	26.355	37.624	79.95	88.05
RM-Mix	26.240	37.796	79.60	88.46

B. Fresh properties of SCC mixtures

The properties of the fresh SCC mixtures were evaluated by the slump flow and the J-ring tests. A slump flow value of 600–750 mm is often targeted for normal SCC mixtures. The amount of super plasticizer required for each mixture to meet the target flow value is presented in Table 5 and Fig. 4. As seen in Fig. 4, with an increase use of the red mud, an increased amount of super plasticizer was required. This might be the fact that the porous red mud had a higher water absorption property (Ahmadi and Shekarchi, 2010, Ahmadi, 2007, Shekarchi et al., 2008, Najimi, 2010, Valipour et al., 2013, Bilim, 2011, Jana, 2007, Tokushige et al., 2009, Uzal et al., 2007), rendering less water available for the slump flow. Thus, for a given w/c, in order to achieve the target slump flow, extra amounts of super plasticizer had to be incorporated to compensate for the water absorbed by the red mud.

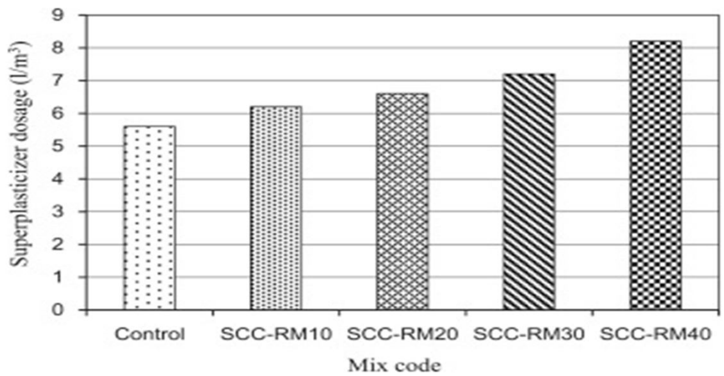

Fig. 4. Fluidity (% of SP) of control and SCC mixtures.

The effects of the red mud replacement level on the workability of SCC mixtures are shown in Table 7. The slump flow diameters (d) of all the SCC mixture samples achieved the target value. The slump flow diameters decreased slightly with the increase in red mud content. Similar results were obtained by Najimi et al. (2012) on their studies on the durability properties of concrete containing zeolite. However, it should be noted that the replacement of fly ash by red mud strongly decreased the segregation. When the red mud replacement was increased from 10% to 40%, the segregation ratio was obviously reduced from 13.5% to 6.0%. This might be attributed to the increased cohesiveness of SCC mixtures with a corresponding increase of the red mud content.

Table 7. Workability of SCC-RM mixtures.

Mix code	Slump flow			J-ring, d (mm)	L-box, ratio (%)	Segregation, ratio (%)
	d (mm)	t_{500} (s)	t_d (s)			
Control- II	750	3.70	34.7	735	0.91	13.5
SCC-RM10	730	4.0	36.0	690	0.90	10.0
SCC-RM20	710	3.6	35.0	700	0.90	10.1
SCC-RM30	700	4.9	38.0	685	0.86	9.0
SCC-RM40	705	6.6	42.3	650	0.85	6.0

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C. Hardened Properties of SCC Mixtures

1) Hardened Density

Fig. 5 shows the effects of the red mud replacement on the hardened density of the SCC mixtures. The hardened density slightly decreased with increasing red mud content at all curing ages. For 28 days curing time, the maximum density of 2393 kg/m^3 was recorded for the control sample (0% red mud), whereas the minimum value of 2361 kg/m^3 was recorded for the 40% red mud (SCC-RM40) sample. Using these two mixtures as examples, the average density of SCC mixture samples was reduced by about 0.4% for every 10% red mud replacement. The density reduction was probably due to the red mud having a lower specific gravity than that of fly ash.

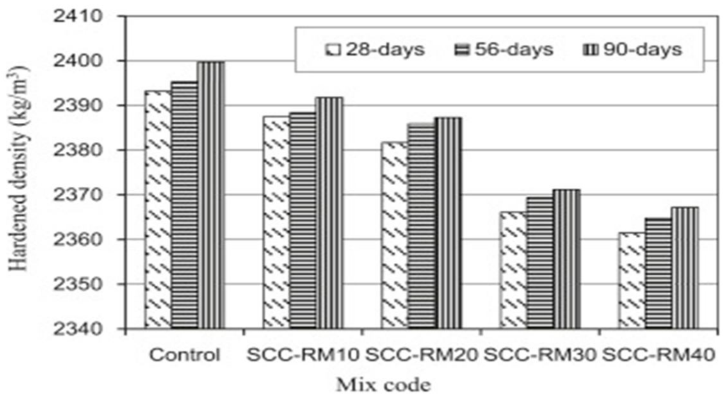

Fig. 5. Effects of the red mud on the hardened density of SCC mixtures.

2) Water Porosity

The results of the porosity determination of the SCC mixtures are given in Fig. 6. The porosities of SCC mixtures prepared with 10–30% red mud content were similar to the control. However, at 40% of red mud replacement, the porosity of the mixture was significantly increased. This is similar to the results of Poon et al. (1999), who reported that when less than 25% zeolite was used in cement pastes, a lower porosity was attained but when the replacement was at 25%, the porosity was increased at all the studied ages. This might be attributed to the fact that with excessive zeolite (red mud) contents, the viscosity of SCC mixtures increased.

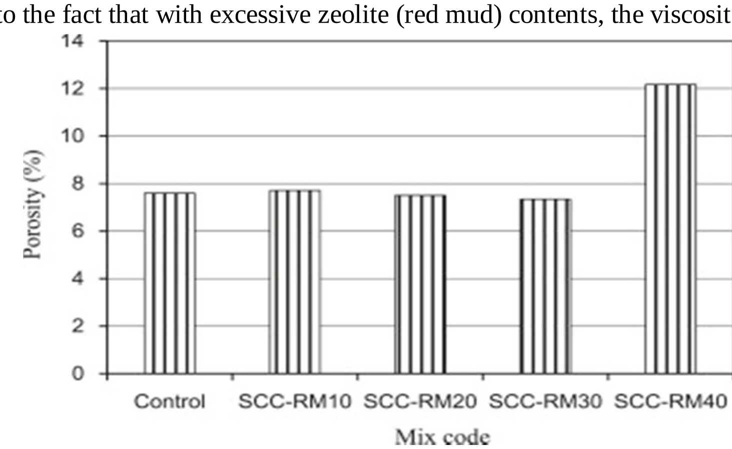

Fig. 6. Effects of the red mud on the porosity of SCC mixtures at 28 days curing.

3) Compressive Strength

The 7, 28, 56, and 90 days compressive strength of the SCC mixture samples are shown in Fig. 7. The results show that the SCC mixtures prepared with the red mud incorporation had similar compressive strength to that of the control at 7 and 28 days. However, at 56 and 90 days, the effects of red mud content on enhancing compressive strength were more pronounced for SCC-RM30 and SCC-RM40. The strength of the SCC mixture samples containing 30% and 40% red mud were 89.4 MPa and 90.1 MPa, which were 8% and 9% higher than the control sample at 56 days, respectively. Also, this trend continued at 90 days. The gain in strength in the two longer curing ages of the higher red mud dosage mixes might be attributed to the internal curing provided by the red mud.

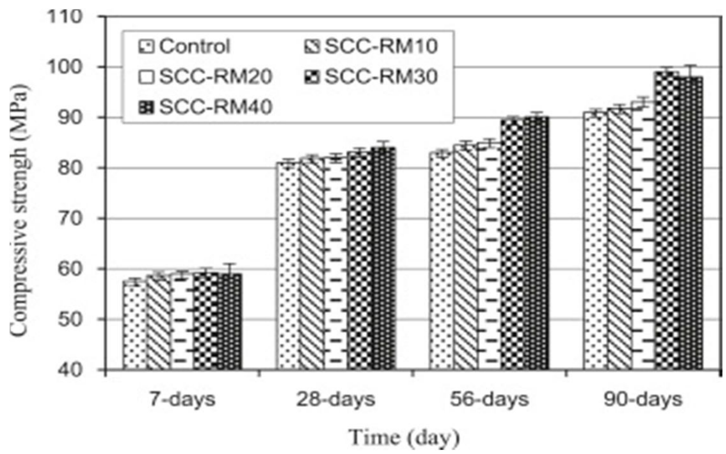

Fig. 7. Compressive strength development of SCC-RM mixtures.

4) Tensile Splitting Strength

Fig. 8 shows the tensile splitting strength for all the SCC mixture samples at 28, 56 and 90 days curing time. The results show that although the tensile splitting strength was slightly lower than that of the control sample for SCC-RM10 and SCC-RM20 at 28 and 56 days, it was obviously enhanced at 90 days. This might be due to the internal curing offered by the red mud. The observation is consistent with the results presented in Fig. 7.

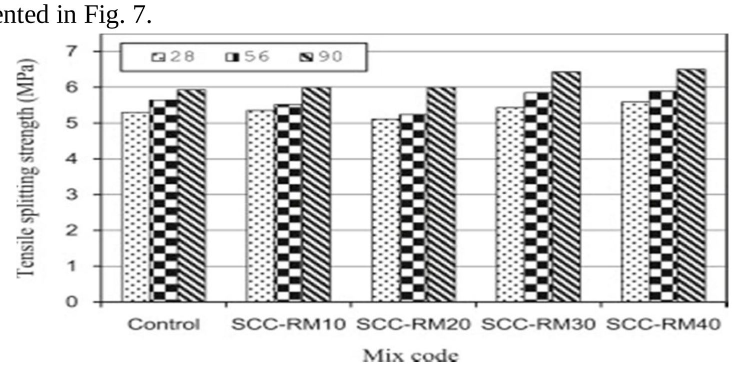

Fig. 8. Tensile splitting strength of SCC mixtures.

5) Elastic Modulus

The effects of the red mud content on the elastic modulus of the SCC mixtures at 28 days are illustrated in Fig. 9. It can be seen that with increasing red mud content (from 0% to 30%), the elastic modulus gradually increase. Based on the results, it can be concluded that red mud have no negative effects on elastic modulus of the SCC mixtures.

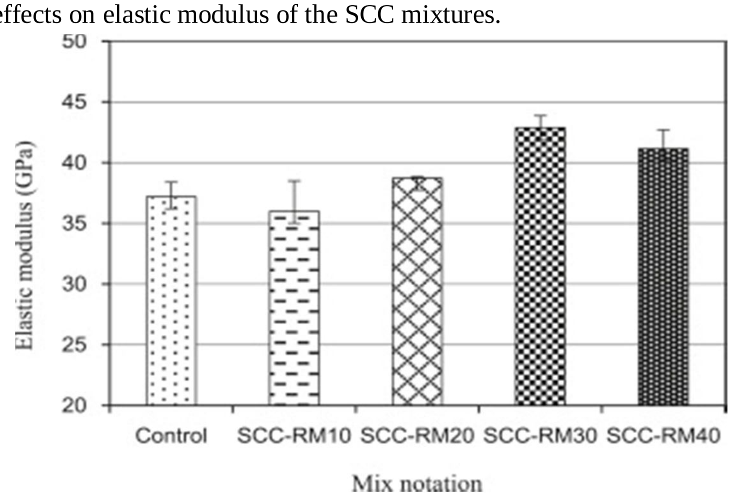

Fig. 9. Elastic modulus of SCC-RM at 28 days curing.

6) Drying Shrinkage

Fig. 10 shows the length change (drying shrinkage) with time for all the SCC mixtures. All the SCC mixtures yielded approximately comparable length change values at the early age of 3 days. After 7 days, a clear distinction was observed between the SCC mixes prepared with different contents of red mud. It is noticed that the SCC mixture samples with red mud had lower drying shrinkage values than the control sample. This beneficial effect is more pronounced with increasing replacement levels of red mud. This is similar to the results of Ahmadi and Shekarchi (2010). Akbar et al. (2013) reported that the shrinkage values of the concrete containing 15% and 30% zeolite were significantly lower than that of the control sample. The possible reason for this might be attributed to the internal curing ability of the red mud. Red mud being a porous material absorbed a large amount of free water in the fresh state but the water gradually migrated from the red mud for concrete curing particularly after the concrete had been dried for some time. This phenomenon is well-documented for concrete mixtures incorporating lightweight aggregates (Ovler and Jensen, 2007, Weber and Reinhardt, 1997, Holm and Bremner, 2000, Villarreal and Crocker, 2007).

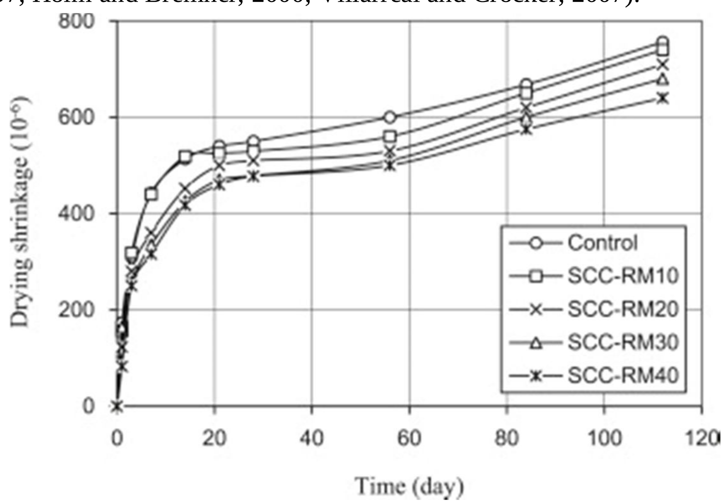

Fig. 10. Drying shrinkage development of SCC mixtures.

IV. CONCLUSIONS

The pozzolanic activity and the effects of the red mud on properties of SCC have been assessed in the present study. The results show that the red mud has good pozzolanic activity roughly equivalent to that of FA. Also, the red mud slightly reduces the flowability and passing ability of SCC; however, the added red mud enhances the viscosity of SCC and significantly prevents segregation and bleeding. The results from the effects of the red mud on the hardened properties of SCC show that the hardened density slightly decreases with increasing red mud content; meanwhile, as the red mud content is 30%–40% of that of FA, enhanced compressive strength and splitting tensile strength of SCC are observed after 90 curing days. In addition, with the addition of the red mud in SCC, the drying shrinkage is reduced, which might be due to the internal curing effect.

Overall, the results of this study have demonstrated that it is feasible to utilize 10%–40% of the red mud to replace FA in the production of SCC.

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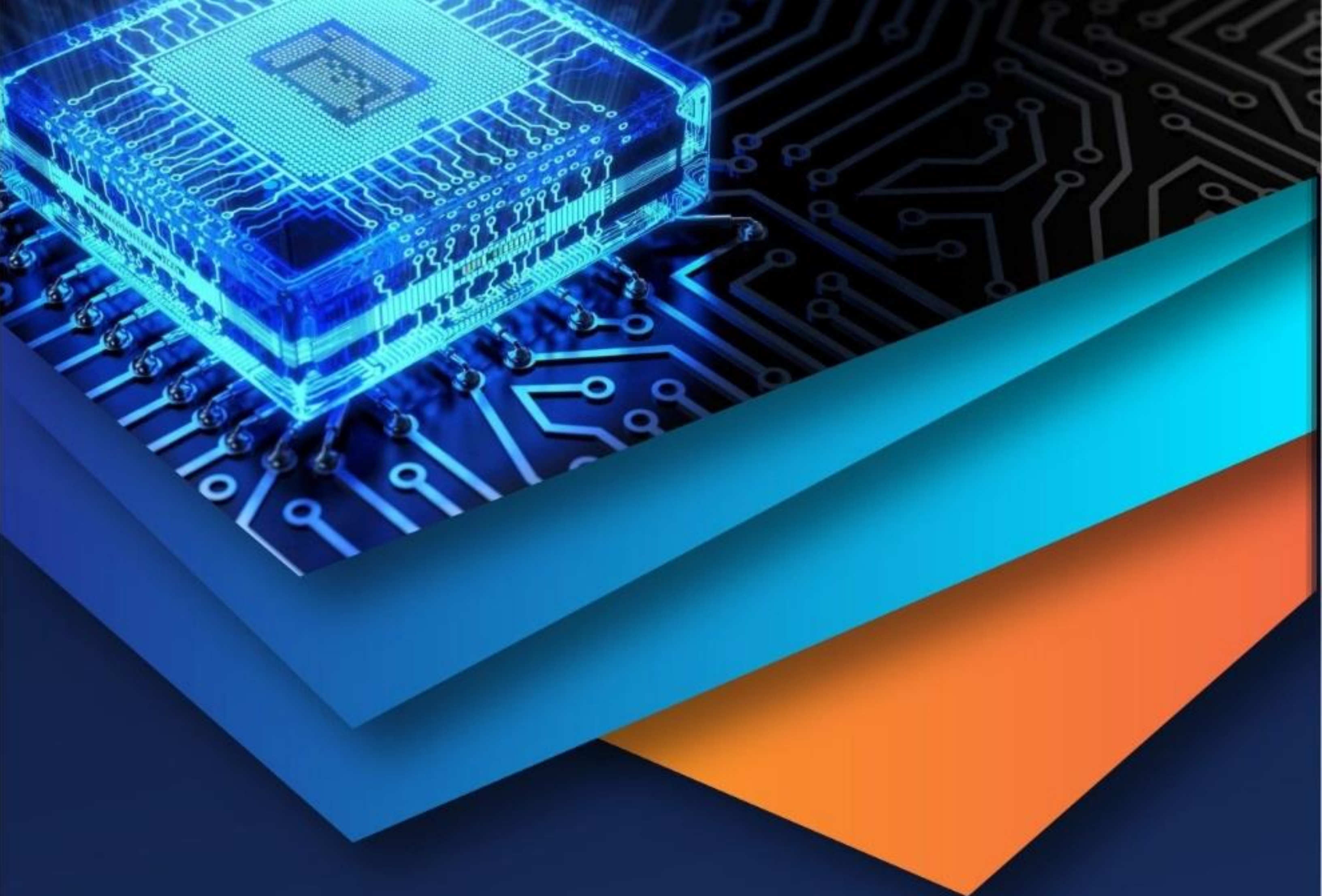

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