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Performance of steel slag and steel sludge in concrete

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HIGHLIGHTS

- We investigated the performance of steel slag and steel sludge in concrete.
- Pozzolanic properties of steel slag and steel sludge were evaluated.
- Inclusion of steel slag and sludge into concrete improve its properties.
- Up to 20% steel slag and 15% steel sludge could be used in concrete.

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ABSTRACT

The impact of environmental cleansing through inclusion of hazardous wastes in cement related products cannot be overemphasized. This paper presents outcomes of laboratory experiments on the utilizations of electric arc furnace steel slag and steel sludge (by-products from steel making industries) as cement replacements in concrete. Pozzolanic properties of steel slag and steel sludge were evaluated using pozzolanic activity test specified by ASTM C618. In addition, the materials were subjected to X-ray Fluorescence and X-ray Diffraction tests in order to identify their chemical as well as mineral compositions respectively. In the process, conductivity of materials suspension in calcium hydroxide ($Ca(OH)_2$) solution were monitored. Mechanical properties of the concrete containing the steel slag and steel sludge were also evaluated. The results of pozzolanic activity tests show that steel sludge has a higher reactivity due its higher loss of conductivity which is about 72.9% as against 43.3% for steel slag. However, both materials show good reactivity in $Ca(OH)_2$ solution. In fact, the strength activity index of both materials were observed to reach a minimum of 75% based on ASTM C618 requirement. Eventually, compressive strength development in concrete due to inclusion of 15% and 20% steel sludge and steel slag respectively yielded higher strength gains over the control mix particularly at later curing ages.

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1. Introduction

Utilization of industrial by-products in concrete have been receiving more attention from researchers. Industrial by-products improve the properties of blended cement concrete and also reduce the environmental problems. Inclusion of wide range of solid wastes such as steel scraps, Ground Granulated Blast furnace Slag (GGBS) and Palm Oil Fuel Ash (POFA) as cement replacement materials in concrete could in addition to mechanical and durability improvements promote environmental cleansing from hazardous materials and massive waste disposal [1–4].

Industrial by-products and waste materials are being generated by various factories including the steel industry. According to Das et al. [5], 2–4 tons of wastes are produced during the manufacture of every single tonne of steel. Although a large amount of the wastes from the steel industry are used in other applications, there is still about 35% unused slag dumped as waste [6]. This is a substantial amount considering the problems posed by these wastes, which may contain significant amount of heavy metals.

By-products from steel industry comes in various forms such as steel slag and steel sludge. In particular, the steel slag is generated at three different stages during processing and consequently categorized as: blast furnace slag, electric arc furnace slag and ladle slag [7]. Meanwhile, except in the production of ceramics, there are no intensive works on the possibilities of consuming these

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wastes in concrete productions. In fact, according to Muhmood et al. [7] and Anif [8], studies on these materials as cement replacements in concrete are scarce in literature. The former examined the integration of Electric Arc Furnace Steel Slag (EAFS) and Ground Granulated Blast Furnace Slag (GGBS) to explore the pozzolanic and cementitious behaviors of the combination. The compressive strength was not affected by the integration of 20% EAFS and GGBS especially at curing ages beyond 28 days.

Luxan et al. [9] studied the characteristics of slag produced in the fusion scrap steel and the results showed that, the presence of anhydrous silicate may cause harm to hydraulic activity. However, according to the report, there are no adverse factors for the use of the slags and no problems of disintegration, cracking, or dimensional instability was observed. Alternatively, other researchers [10–14] propose the potential use of EAFS as aggregate. In fact, a successful use of EAFS as road base material had been studied by Wu et al. [15] and Pasetto & Baldo [16].

Generally, steel sludge on the other hand has been regarded as fine solid substances recovered after wet cleaning of gas which usually emerge in form of sludge during the production of steel. In the process, fine iron oxide particles were removed by wet scrubbing. Vieira et al. [17] studied the performance of steel sludge in the production of red ceramics. The results showed that incorporation of 5% by weight of fine steel sludge into clay was useful to the red ceramics, and at 20% by weight, the porosity decreased when compared with the pure clay. Meanwhile, in the last few decades, to the best of our knowledge, no specific study was performed on the utilization of steel sludge in concrete.

This paper presents research findings on the performance of steel slag and steel sludge in concrete through evaluations of their pozzolanic activities, X-ray Fluorescence (XRF) and X-ray Diffraction (XRD) tests, thermogravity analyses, properties of fresh mixes and hardened concrete which includes; compressive strengths, indirect tensile strengths, flexural strengths and modulus of elasticity. Conductivity method and ASTM C618 [18] were employed for the evaluations of the pozzolanic activities. Indeed, inclusions of steel slag and steel sludge in concrete with its high annual volume of production will add to concrete sustainability and these could provide better solutions to the environmental against waste disposal.

2. Materials and methods

2.1. Materials

ASTM Type-1 Portland cement was used throughout. The other main materials are steel slag, steel sludge, aggregates and water for mixing. Chemical compositions of the cement, steel slag and steel sludge are shown in Table 1. Dry mining sand passing 5 mm sieve size and crushed granite of maximum size 10 mm were used as fine and coarse aggregates respectively. The fine aggregate has a fineness modulus of 2.4. However, graded sand of grain size between 600 μm and 150 μm was used in mortar mix for the strength activity index.

While the steel slag was generated from the process of melting metal scrap in an electric arc furnace, the steel sludge was however generated from steel wire production. The slag was collected and cooled to ambient temperature in an open atmosphere at the production site. The sludge on the other hand was generated during the process of remoulding the steel wires to assume desired shapes and sizes. Both materials were prepared by grinding to 45 μm fineness. While the steel slag undergoes no further drying before grounding to fine particles as it was completely dried during cooling to ambient temperature, the steel sludge was introduced to oven for drying as it was wet and sticky when delivered. The sludge was dried at 105 °C for 24 h before undergoing the grinding process. Figs. 1 and 2 show the steel slag and steel sludge as received, crushed and ground forms.

Table 1
Oxide composition of cement, steel slag and steel sludge.

Material (%)	Oxide composition						
	Fe_2O_3	SiO_2	CaO	Al_2O_3	MnO	MgO	Na_2O
Cement	3.53	16.4	68.4	4.24	0.15	2.39	Nil
Steel slag	43.4	26.4	16.9	4.84	2.66	1.86	0.15
Steel sludge	71.9	4.13	2.26	0.53	0.67	3.59	6.16

2.2. Mix-design

The main types of mixes and mix-designs involved in this research are shown in Table 2. The target mean strength for the designed mix proportions is 35 MPa at 28 days.

2.3. Pozzolanic activity test

Pozzolanic activity test entails rapid evaluation of pozzolanic properties of materials and it monitors conductivity of Pozzolanic material suspension in calcium hydroxide ($Ca(OH)_2$) solution. The test was conducted on both the steel slag and steel sludge following the procedure suggested by Paya et al. [19]. The test was carried out through preparation of an unsaturated ($Ca\,(OH)_2$) solution in a beaker using solution of 200 mg of analytical-grade ($Ca(OH)_2$) in 250 ml of deionized water at 40 ± 1 °C. A 5 g of the test material was added to the beaker following the lime–water system so that a permanent conductivity is achieved. The solution was continuously mixed by a magnetic stirrer up to the end of the test. In a similar manner, the test was carried out again for the steel sludge.

The electrical conductivity and pH of the solution were measured by a digital conductivity-meter and a pH meter respectively. The data was recorded at time intervals. The same method was applied for the pozzolan–water systems at 40 ± 1 °C. To achieve this goal, 5 g of Pozzolanic material was added in 250 ml of deionized water. The Pozzolanic material was allowed to react with water as suggested by Paya et al. [19] in order to eliminate the variation in conductivity due to high salinity of the material.

The pozzolanic activity test was repeated three times for each specimen aimed at establishing better results. Measurements of the conductivity were corrected through elimination of the influence normally caused by soluble salt. The correction was achieved by subtracting the pozzolan–lime conductivity from the pozzolan–water conductivity [19].

2.4. Standard specification for pozzolan (ASTM C618)

Pozzolanic properties of steel slag and steel sludge were tested according to ASTM C618. Broadly, there are two standard requirements to satisfy pozzolanic characterizations which are chemical and physical. For the chemical requirements, the tests conducted are moisture content, as well as summation of SiO_2, Al_2O_3 and Fe_2O_3 percentages. For the physical requirements, the tests are fineness, and strength activity index.

While the fineness of the materials were checked by 2.36 mm sieve, the strength activity index was conducted using 50 mm mortar cube specimen in accordance with ASTM C311. Control and design mix specimens were placed in metal moulds. For the design mixture, 20% of the mass of cement was replaced with the test sample. However, water-binder ratio (w/b) of 0.48 was employed. After casting, the specimens were placed in moist room at 23.0 ± 2 °C for 24 h. Then, the specimens were removed from the moist room, remoulded and placed in a saturated lime solution until the proposed ages of tests (7 and 28 days).

2.5. The X-ray fluorescence and X-ray diffraction tests

The steel slag and steel sludge were subjected to XRF test in order to identify their oxide compositions as shown in Table 1. Furthermore, XRD test was conducted to also determine the mineral compositions of these materials.

2.6. Thermogravity test

To study the hydration of cement containing the steel slag and the steel sludge separately, cubes of 50 mm × 50 mm × 50 mm cement pastes were casted. The specimens were cured in water for 3, 7, 28, 60 and 90 days. At the end of each particular curing age, specimens were crushed into small pieces and put into the oven for 24 h in order to remove all existing moisture. Eventually, the dried specimen pieces were grounded to 45 μm.

2.7. Workability test

Work abilities of fresh concrete mixes containing steel slag and steel sludge were evaluated through slump tests. The test employed was in accordance with BS 1881: Part 102; 1983 [20]. The water–cement ratio used was 0.58. All slump tests were conducted immediately after mixing.

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