Strength and performance of reinforced incinerator bottom ash concrete cube

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Abstract. Municipal solid waste incineration produces non-combustible by-product known as bottom ash. Increase in waste production leads to increase in bottom ash, which raises environmental concerns and management issues. With the parameters and properties of bottom ash are in close agreement with those of aggregates used in concrete making, bottom ash has been adopted for reutilization in civil engineering. However, the workability of the concrete made with partial substitution of aggregate with bottom ash from local municipal solid waste incinerator has never been addressed. This paper aims to evaluate the performance and properties of concrete cube made with partial substitution of aggregate with bottom ash from Pulau Pangkor municipal solid waste incinerator in Perak. The content of bottom ash substitution in concrete cube made in this study were varied at 10, 20 and 30 percent of aggregate. All samples were tested for its workability, water absorption, compressive strength, and resistant towards fire. It was found that the performance of concrete with partial substitution of aggregate with bottom ash reduced with increased in substitution content in all aspects. However, the performance of the concrete with 10 percent bottom ash substitution to aggregate was acceptable and closed to that of control concrete. It has been demonstrated through this study that the use of bottom ash as partial substitution of aggregate in concrete making is possible at very low content. However, there are huge needs of further enhancement in manufacturing methodology in order to produce concrete with partial substitution of aggregate with bottom ash that outperform – or in closed agreement with – the control concrete.

1. Introduction

In 2012, Malaysia produced more than 25,000 tonnes of waste daily [1]. This amount is expected to forge ahead as the life expectancy improved and the population growing. Waste management issues such as paucity of environmental concerns, habitual single-utilization, and ignorance worsen this situation even further.

Incineration of municipal solid waste produces bottom ash among others, which usually will be disposed off in a landfill. While landfiling can be cost-effective and painless, the landfills contribute to the rising of social and environmental nuisance [2-4]. Thus, reducing and limiting landfiling are promoted, which includes waste-to-energy incineration, anaerobic digestion, composting, mechanical biological treatment, pyrolysis and plasma arc gasification. In 2017, the National Solid Waste Management Department (JPSPN) promoted waste-to-energy technology and business model to be incorporated into Malaysia waste management system, in which the resultant incinerator by-products...
are proposed to be recycled for construction materials [5]. The used of bottom ash as secondary building material is encourage to limit the use of natural aggregates whilst avoiding excessive landfilling.

Reutilization of bottom ash after natural weathering of at least two months is considered non-hazardous according to the European Landfill Directive [6]. Recently, a group of researchers in China has been evaluating prepared autoclaved aerated concrete with municipal solid waste incineration bottom ash to substitute quartz sand [7]. The substitution broadened the raw materials range used in the process and improved cost-effectiveness. The benefit demonstrated in the study were also found in another work on cement composite [8]. Meanwhile, the Italian researcher found that recycling bottom ash as aggregates for concrete exhibited proportionate mechanical properties to those of control concrete [9]. The same behaviour was also found in substituting clay with municipal solid waste incinerator bottom ash in the production of fired bricks [10]. All these promising prospects of recycling municipal solid waste incinerator bottom ash inspired the present work, in which the performance and properties of concrete with partial substitution of aggregate with local municipal solid waste incinerator bottom ash is investigated.

2. Materials and Methods

2.1 Characterisation of materials

The bottom ash was gathered from a local municipal solid waste incinerator in Pulau Pangkor, Perak, Malaysia. The facility is capable of incinerating 20 tonnes of municipal solid waste daily. However, the bottom ash produce from the incinerator are not reused for any secondary applications. The amount of bottom ash collected from the facility was around 200-300 kg. The bottom ash had been naturally weathered for at least three months prior to the collection date and homogenised using a sift. About 1 kg of the bottom ash was used for characterisation. X-Ray Fluorescence Spectroscopy (XRF) (ARL™ 9900 Thermo Fisher Scientific, USA) was used to find the major chemical elements in bottom ash (Table 1, in comparison to the elemental constituents of cement). The particle size and density of the bottom ash were evaluated according to EN 933-2 [11] and EN 1097-6 [12], respectively.

| Element | Cement Percent (%) | Bottom Ash Percent (%) |
|---------|---------------------|------------------------|
| Al      | 2.900               | 4.070                  |
| Si      | 13.40               | 9.590                  |
| S       | 3.430               | 2.450                  |
| K       | 1.120               | 2.830                  |
| Ca      | 73.47               | 63.94                  |
| Ti      | 0.340               | 1.920                  |
| V       | 0.070               | 0.000                  |
| Cr      | 0.035               | 0.120                  |
| Mn      | 0.200               | 0.260                  |
| Fe      | 4.470               | 10.00                  |
| Cu      | 0.034               | 0.274                  |
| Sr      | 0.051               | 0.410                  |
| Zr      | 0.025               | 0.120                  |
| Ru      | 0.200               | 0.560                  |
2.2 Method

The ordinary Portland cement (OPC) was used for concrete cast at 1:4 ratio to aggregate material in all sample. The particle size of the OPC was 3.9 µm with specific gravity of 3.01. The chemical composition of the OPC is tabulated below in Table 2. The used of bottom ash as partial substitution for the aggregate was ensure not to exceed 30% in weight. The concrete making process was done according to ASTM C192/C192-16a [13]. Three cubic samples with dimension of 10 cm x 10 cm x 10 cm were cast for each formulation (10%, 20% and 30% in weight of bottom ash). All samples were tested and compared against control concrete using 100% natural gravel as aggregate.

Table 2. Chemical constituents of OPC.

| Constituent        | Percentage |
|--------------------|------------|
| SiO₂               | 21.25 %    |
| Al₂O₃              | 5.04 %     |
| Fe₂O₃              | 3.24 %     |
| CaO                | 63.61 %    |
| MgO                | 4.56 %     |
| Loss on ignition   | 3.26 %     |

Post-cast concrete samples were then kept in the climatic chamber for 24 h. To measure the consistency of the concrete samples, slump test was conducted in accordance to ASTM C143/C143-15a [14]. All samples were then stored in the curing room with ambient temperature for 28 days, followed by compressive strength test [15] using universal testing machine (TEST-E series, Test International, UK). Further, the susceptibility of the concrete against water penetration was tested for all sample in reference to ASTM C1585-13 [16]. This is relevant to various aspect of durability of the concrete. The density of the hardened concrete cube samples were also computed. The fire performance of the concrete samples was evaluated according to ASTM STP882 [17].

3. Results and Discussion

Table 3 shows the type of slump and slump produced by the samples (p > 0.05). The samples subjected to slump test produced slump in the range of medium workability mixes (50 mm – 90 mm slump), which are appropriate for normal reinforced concrete [18]. The concrete subsides with retained shape in all samples. The sample slump was found to be directly proportional to the amount of bottom ash used as partial substitution of aggregates in the samples, therefore the higher the bottom ash content in a concrete cube, the higher its workability.

Table 3. Resultant consistency of the samples before set.

| Concrete samples | Mean slump (mm) | Type of slump |
|------------------|-----------------|---------------|
| Control          | 52              | True slump    |
| 10% BA           | 55              | True slump    |
| 20% BA           | 60              | True slump    |
| 30% BA           | 77              | True slump    |

The ability of the concrete to absorb water is depending on its permeability, porosity and the strength of capillary forces [19]. Low value of water absorption indicates for good resistance to the natural environment and good permeability. Low permeability of concrete allows for chemical attack by penetration of various ions and other harmful substance. From the results shown in Figure 1, it is clear that the environmental resistance and permeability of concrete samples improved with increase in bottom ash content as partial substitution of aggregate. Thus, the partial substitution of aggregate with bottom ash enhance the aggregate-cement paste interface within the concrete sample and it gets better
with better curing condition [19]. This result implies that the concrete samples with the highest bottom ash content perform best in terms of compressive strength, permeability, resistance to sulfate attack, and chloride ion diffusion.

The mechanical strength and durability of concrete are highly influenced by its density. Table 4 shows the weight and density recorded for concrete samples on the 7th and 28th curing day. The average density of concrete samples tested in this study was found to be improved with curing time. High density concrete exhibits high mechanical strength with less voids and pores. Therefore, less water penetration is allowed making the concrete durable. However, all concrete samples with bottom ash content as partial substitution of aggregate demonstrate density lower than the control concrete samples. This is due to lesser weight exhibit by samples with bottom ash content. In general, concrete samples with bottom ash content are expected to absorb more impact energy than the control concrete samples [20, 21].

**Figure 1.** Water absorption value for all samples at various content of bottom ash.

![Water absorption value for all samples at various content of bottom ash.](image)

**Table 4.** Recorded mean density of all samples on the 7th and 28th curing day.

| Sample | Day | Weight after curing (kg) | Mean density of sample (kg/m³) |
|--------|-----|--------------------------|--------------------------------|
|        |     | Sample 1  | Sample 2  | Sample 3  |                        |
| 30%    | 7   | 3.485     | 3.602     | 3.495     | 3527.3                |
|        | 28  | 4.580     | 4.670     | 3.550     | 3600.0                |
| 20%    | 7   | 3.390     | 3.590     | 3.890     | 3623.3                |
|        | 28  | 3.490     | 3.620     | 3.950     | 3666.7                |
| 10%    | 7   | 3.640     | 3.900     | 3.940     | 3826.7                |
|        | 28  | 3.669     | 4.080     | 3.950     | 3859.7                |
| 0%     | 7   | 3.880     | 3.890     | 4.101     | 3957.0                |
|        | 28  | 3.904     | 3.901     | 4.108     | 3971.0                |

Compressive strength of the concrete samples portrays the overall quality of concrete and the structure of cement-paste within. The properties of aggregates affects the compressive strength of the concrete, it is expected that the compressive strength of concrete samples with bottom ash content is
lower than the control concrete samples. The phenomena were observed in all concrete samples regardless of the curing age (Figure 2). Higher content of bottom ash in the concrete samples is found to worsen its compressive strength. The compressive strength was also found improved with prolonged curing age in all samples. However, all samples exhibit the strength within the optimum range for normal field application (10 MPa – 60 MPa) [21].

![Figure 2. Mean compressive strength of the concrete cube over curing age on 7th and 28th curing day.](image)

Concrete is considered fire resistant, non-combustible and exhibit low heat-transfer rate. Concrete has been used to minimize the risk of fire with the least cost and maintenance required. However, there were some instances such as fire in tunnels had drawn interest on the robustness of all construction materials in fire, concrete included. At elevated temperature (450 °C – 600 °C), the concrete may lose moisture and deteriorate its strength [22]. Different types of aggregate may as well affected the maximum temperature range [20, 22]. Figure 3 shows the reduction of compressive strength in all concrete sample after fire resistance test. As expected, concrete samples with the highest bottom ash content demonstrate the lowest compressive strength.

![Figure 3. Mean compressive strength of concrete samples before and after fire resistance test.](image)
4. Conclusions
Partial substitution of aggregate with municipal waste incinerator bottom ash was found to be acceptable for concrete making. However, the overall performance of the concrete samples with bottom ash content is slightly poorer than the control concrete samples evaluated in this study. The optimum content of bottom ash is at 10% substitution by weight. Further substitution (at higher content) was observed to deteriorate the performance even more.

It is clear that the concrete making process with partial replacement of aggregate with bottom ash needs improvement. More evaluation on the properties and performance of the concrete should be considered in the future to better assess the workability of the concrete containing bottom ash.

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