EFFECT OF INCINERATED SUGARCANE BAGASSE IN REDUCING HEAT OF HYDRATION IN CONCRETE

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Incinerated sugarcane bagasse (ISB) is an agro-based industrial waste material which is rich in silica. It has been observed that it has the potential to reduce the heat that will be generated from hydration reaction. Lower rate of heat release and lesser magnitude of heat production during the hydration reaction of cement are desirable properties in mass concreting and production of concrete in hot weather condition. In this study, the heat evolution and tensile strength development of concrete with and without the inclusion of ISB was examined. A systematic volume-based replacement of cement by ISB was made with ISB amount of 10%, 20% and 30%. The hydration kinetics of cement paste with various percentages of ISB was checked using differential calorimeter. In addition, a concrete made with ISB was prepared and the temperature evolution history was traced in an environmentally controlled chamber. The heat generated from a set of concrete samples were studied under a surrounding temperature of 25°C and 50°C. Results obtained from both the differential calorimeter of cement paste and the concrete in the controlled chamber indicate, with the increase of the ISB replacement, the rate of heat release and the amount of heat generation within the mix decreases. In conjunction, with the increase of ISB up to 20% the early-age tensile strength of concrete increases. These two important attributes of adding ISB to concrete signify reduction in the risk of early age cracking in concrete.

Keywords: Mass concrete, Hydration kinetics, Hot weather concreting, Early age thermal cracking, Tensile strength development.

1 INTRODUCTION

Cement hydration is followed by heat generation, formation of pore structures and development of mechanical strength in concrete, mortar and cement paste. Hydration of cement is an essential phenomenon in assessing concrete performance. There exists a strong relationship between heat generation and the degree of hydration of each clinker constituting minerals (Taylor 1997). Depending on the functionality and construction environment of a structure, the quantity of these constituent minerals varies in a cement. In addition, the introduction of additional minerals or binder materials affect the conventional chemical reaction and thermodynamic characteristics of these constituent materials in Portland cement during hydration reaction. Therefore, to achieve the desirable performance requirement, complying with the construction methodology and environment of a certain structure, a modification in the conventional quantity of clinker minerals and or the addition of other binder materials can be options.

Hot weather concreting is accompanied by higher rate of heat production during the hydration of Portland cement. Concreting in arid and semi-arid areas such as in tropical zone is highly
susceptible to this phenomenon. This sharp and rapid increase in rate of heat production will be responsible for early-stage thermal cracking. Similarly, during the construction of mass concrete; due to the thermal gradient between the part of the concrete closer to the outside environment and the most inner part of the concrete, there will be tensile stresses and strains developed due to the volume change associated with the thermo-hygral gradient. Therefore, the aim of this study is to discuss the impact of the addition of incinerated sugarcane bagasse (ISB) in concrete with respect to the above-mentioned problems.

ISB is an agro-based industrial waste material obtained from the residue of the incineration of sugarcane bagasse. Several studies indicated that this material is rich in silica; the chemical composition of ISB contains 60-85% SiO₂ (Shafiq 2016, A. Bahrudeen et al. 2015, Marcela M.N.S. de Soares et al. 2016, Santos et al. 2018, Sharma 2019, Arenas-Piedrahita et al. 2016). The large amount of silica in ISB is a potential for pozzolanic reaction (Justs et al. 2011). The presence of pozzolans reduce the hydration heat rate of C₃S (alite) and C₂S (belite); main clinker phases of Portland cement, due to the reduced calcium ion concentration (Prasath and Santhanam 2013, Bapat 2013). In order to reduce the risk of early age thermal cracking, it is a must to quantitatively estimate the hydration process over time. This study assessed the impact of introducing ISB in concrete in terms of the possibility of reducing the rate and magnitude of heat production during hydration reaction and also the effect of using ISB in early age tensile strength development.

2 MATERIAL AND MIX PROPORTION

2.1 Concrete Ingredient Materials

The ISB used in this study was allowed to dry at room temperature as there was some moisture in it. Then, it was sieved with 300µm sieve and the ISB material which is less than 300µm size is used throughout the entire sets of experiment and material property assessment. The ISB has a specific gravity of 2.235g/cc and specific surface area of 3370cm²/g. The chemical composition of binder materials used in this study is summarized in Table 1. The major oxide of the ISB is SiO₂, which was 67%. The sum of SiO₂, Al₂O₃ and Fe₂O₃ for the ISB is 80.1%, which was higher than the minimum value (70%) specified in ASTM: C618 for natural pozzolan. The cement used was 42.5 grade OPC with specific gravity of 3.15g/cc and specific surface area 3750 cm²/g.

<table>
<thead>
<tr>
<th>Investigated Constituents</th>
<th>ISB (%)</th>
<th>OPC Cement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Dioxide (SiO₂)</td>
<td>66.92</td>
<td>20.82</td>
</tr>
<tr>
<td>Aluminum Oxide (Al₂O₃)</td>
<td>7.06</td>
<td>5.41</td>
</tr>
<tr>
<td>Ferrite (Fe₂O₃)</td>
<td>6.12</td>
<td>3.37</td>
</tr>
<tr>
<td>Calcium Oxide (CaO)</td>
<td>3.6</td>
<td>66.32</td>
</tr>
<tr>
<td>Magnesium Oxide (MgO)</td>
<td>1.96</td>
<td>1.46</td>
</tr>
<tr>
<td>Sodium Oxide (Na₂O)</td>
<td>4.28</td>
<td>-</td>
</tr>
<tr>
<td>Potassium Oxide (K₂O)</td>
<td>4.92</td>
<td>-</td>
</tr>
<tr>
<td>Manganese Oxide (MnO)</td>
<td>0.2</td>
<td>-</td>
</tr>
<tr>
<td>Loose In Ignition (LOI)</td>
<td>3.65</td>
<td>-</td>
</tr>
<tr>
<td>Sulfate (SO₄)</td>
<td>0.25</td>
<td>2.16</td>
</tr>
<tr>
<td>Phosphorus pentoxide</td>
<td>0.19</td>
<td>-</td>
</tr>
<tr>
<td>Titanium oxide</td>
<td>0.16</td>
<td>-</td>
</tr>
</tbody>
</table>

The fine and coarse aggregate materials used in this study have a physical property as shown in Table 2.
Table 2. Physical properties of aggregates.

<table>
<thead>
<tr>
<th>Description</th>
<th>Specific gravity</th>
<th>Unit weight (kg/m³)</th>
<th>Water absorption (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine aggregate</td>
<td>2.48</td>
<td>1620</td>
<td>4.16</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>2.79</td>
<td>1743</td>
<td>0.10</td>
</tr>
</tbody>
</table>

2.2 Mix Proportioning

The mix proportioning for each set of experiment was prepared based on a binary mix design. A systematic replacement of cement with ISB was made by volume. The volume-based replacement ratio was chosen to ensure a constant volume of cementitious material per unit volume of binary mix. Therefore, replacing of 1% volume of cement by equal volume of ISB was found to be equivalent to replacing 0.711% weight of cement with ISB. A water to binder ratio of 0.47 and superplasticizer dosage of 0.5% of the binder by weight was used throughout the entire experiment. The mix proportioning used in the experiment is summarized and tabulated in Table 3 and 4.

Table 3. Mix proportion of concrete.

<table>
<thead>
<tr>
<th>Percentage of replacement</th>
<th>Water (Kg/m³)</th>
<th>Cement (Kg/m³)</th>
<th>ISB (Kg/m³)</th>
<th>Coarse Aggregate (Kg/m³)</th>
<th>Fine Aggregate (Kg/m³)</th>
<th>Admixture - superplasticizer (Kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>190</td>
<td>404</td>
<td>0</td>
<td>1069</td>
<td>690</td>
<td>2.02</td>
</tr>
<tr>
<td>10%</td>
<td>190</td>
<td>364</td>
<td>28</td>
<td>1069</td>
<td>690</td>
<td>1.95</td>
</tr>
<tr>
<td>20%</td>
<td>190</td>
<td>324</td>
<td>54</td>
<td>1069</td>
<td>690</td>
<td>1.89</td>
</tr>
<tr>
<td>30%</td>
<td>190</td>
<td>287</td>
<td>78</td>
<td>1069</td>
<td>690</td>
<td>1.83</td>
</tr>
</tbody>
</table>

Table 4. Mix proportion of cement paste.

<table>
<thead>
<tr>
<th>ISB (%)</th>
<th>Water (gm)</th>
<th>Binder (gm)</th>
<th>Cement (gm)</th>
<th>ISB (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.7</td>
<td>10.00</td>
<td>10.00</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>4.7</td>
<td>9.68</td>
<td>8.99</td>
<td>0.69</td>
</tr>
<tr>
<td>20</td>
<td>4.7</td>
<td>9.35</td>
<td>8.02</td>
<td>1.33</td>
</tr>
<tr>
<td>30</td>
<td>4.7</td>
<td>9.03</td>
<td>7.10</td>
<td>1.93</td>
</tr>
</tbody>
</table>

3 EXPERIMENTAL PROGRAM

The heat of hydration with ISB was investigated using two sets of experiment. The first set was carried out on cement paste with ISB replacement ratios of 0%, 10%, 20% and 30% under adiabatic temperature conditions. The first set is aimed to understand the intrinsic heat evolution property of the cement and ISB. The second set was made on concrete specimens with ISB replacement ratio of 0%, 10%, 20% and 30% inside an environmentally controlled chamber.

In the first set, cement pastes were prepared with a water to binder ratio of 0.47 and a binder material of 10gm for the reference mix. Accordingly, the ISB dosage in 10%, 20% and 30% of replacement was proportioned as summarized in Table 4. The ISB and cement were homogenized well before they got introduced into sample holder. The calorimetry setup is illustrated in Figure 1(Right).

An endeavor was made to build an adiabatic condition in an environmentally controlled chamber to study the thermal response of concrete with ISB at two different chamber
temperatures. The chamber has an internal dimension 3m*1m*1.4m and it can accommodate two concrete samples of size 50cm*40cm*40cm. A concrete sample without and with various dosages of ISB was prepared and molded in a form made of plywood and Styrofoam. These materials were chosen as they have a better heat insulating capacity. In each sample, three temperature sensors are embedded in the fresh concrete. Along the depth, 50cm, the sensors were embedded at a depth of 7.5cm from the very bottom and top of the concrete and at 25cm. The chamber’s temperature was kept constant using a heater and a temperature sensor which regulates the temperature in coordination. In this experiment, chamber temperatures of 25°C and 50°C were used in order to represent a moderate and severe environmental condition. Concrete casting was carried out at laboratory conditions.

A control unit which monitors the embedded temperature sensors inside the concrete, the heaters, a sensor which senses the temperature and humidity of the chamber was arranged in a manner as shown in Figure 1 (Left).

4 RESULTS AND DISCUSSIONS

The recording of heat evolution rate and accumulated heat in the adiabatic calorimeter was made continuously for the first 75 hours (3days and three hours). The evolution of heat rate for the four set of cement paste samples and the accumulated heat are depicted in Figures 2 and 3. The data indicates an obvious decreasing trend in heat evolution rate as the amount of ISB increases within the cement paste. The accumulated heat per unit mass after 75 hours gradually decreases with the increase of ISB replacement in proportional manner from 280J/g for the pure OPC paste sample to 217J/gm for the cement paste with 30% ISB. These results clearly indicate that the early-age hydration heat generation of cement paste with partial ISB replacement is lower, highlighting a promising potential for reduced risk of early-age cracking in concrete.
Similarly, the temperature history of concrete samples recorded at 25°C and 50°C chamber temperature were also showing the same trend of temperature profile. Comparing the temperature data of concrete for each set of samples with their respective depth of investigation is showing a decrease in temperature with the increase in amount of ISB i.e. the bottom temperature of a concrete sample with 0% ISB is greater than the bottom temperature of concrete sample with 30% ISB at a given time within either a chamber temperature of 25°C or 50°C. Recording was made continuously for 3.75 days. The evolution of temperature recording can be seen from the graph in Figure 4. Similar trends were also observed for the top and bottom temperature measurement.
In order to assess the early-age cracking risk, the evolution of early-age tensile strength must also be assessed in conjunction. The tensile strength development was checked using a third point loading and the corresponding results are tabulated in Table 5.

Table 5. Temperature and strength development of concrete.

<table>
<thead>
<tr>
<th>ISB (%)</th>
<th>Tensile strength Mpa</th>
<th>Max middle depth temperature at 25°C (°C)</th>
<th>Max middle depth temperature at 50°C (°C)</th>
<th>Time at which max middle depth temperature attained (25°C) (days)</th>
<th>Time at which max middle depth temperature attained (50°C) (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>2.97 5.77 6.67</td>
<td>52.00 58.00</td>
<td>1.03 1.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>2.93 6.30 6.92</td>
<td>49.00 55.00</td>
<td>1.07 2.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>3.03 6.58 6.93</td>
<td>47.00 52.50</td>
<td>1.09 2.40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30%</td>
<td>2.80 4.32 5.57</td>
<td>45.00 50.00</td>
<td>1.12 3.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

5 CONCLUSION

In this study the hydration kinetics of concrete and cement paste was examined with various dosages of ISB. While contributing to the efforts being made towards the development of low-carbon concrete, the results indicated that, the inclusion of ISB in concrete and cement pastes leads to lower rate of heat release (by 27% at a dosage of 30%) and reduces the amount of heat generated (by 23% at a dosage of 30%) due to early-age hydration reaction. Complementarily, the introduction of ISB in a concrete was showing a better tensile strength development up to a replacement of 20% with slight decrement at 30%. These, reduced heat generation and improved early-age tensile strength, attributes of introducing ISB in a concrete has meaningful advantages in terms of reducing the possible risk of early-age thermal cracking, thereby contributing to the durability and reduced carbon-foot print of concrete.

References


Bapat, J. D., Mineral Admixtures in Cement and Concrete, Taylor & Francis, 2013.


