Ferrosilicate slag from zinc production as aggregates bound in cement

Name: Trial Concrete road at Britannia Zinc Limited (BZL)

Region: South West

Type of project: Demonstration (Research trial)

Date: September 2002
Background Information

History
Until early 2003 the BZL works was the UK’s only primary zinc smelter and had been at the site at Avonmouth, near the Severn Estuary, for 50 years. BZL was able to supply the zinc market with a range of grades and qualities through the development of the ‘Imperial Smelting Process’ to produce on average 90,000 tonnes of zinc and 35,000 tonnes of lead a year[1]. However the zinc production process at BZL, Avonmouth, also produced 80,000 tonnes per annum of ferro-silicate slag (Imperial Smelting Furnace slag, ISF slag) as a by-product. Ferro-silicate slag was produced and landfilled until March 2003 (when BZL ceased zinc production) and, at the time of writing, there are still significant quantities of this material (2 Mt stockpiled/landfilled) available at the Avonmouth site [1] (See Figure 1).

Figure 1 Zinc slag stockpile at BZL, Avonmouth

The project
A previous feasibility study undertaken by BRE [2] highlighted the potential use for ferro-silicate ISF slag from zinc production as aggregates bound in cement or bitumen. Additionally, laboratory studies at BRE showed the technical feasibility of using these waste streams in construction.

The BRE-led project described in this case study focused on development of concrete mixes containing the ISF slag. The concrete mix designs developed in the laboratory were then demonstrated in-situ through the construction of road sections on the Avonmouth site.
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The programme also included laboratory based leaching tests and on-going monitoring of the trial road sections on the Avonmouth site.

Specific issues associated with the use of ISF slag in construction have been investigated and addressed during this project. These include:

- the potential to leach over time, and consequent environmental considerations,
- delayed set times when used in relatively high proportions in concrete, apparently related to the presence of lead and zinc,
- colour, which can influence the finished appearance of concrete mixes.

Background to ISF slag

ISF slag is a by-product, generated during the primary smelting of zinc ore in a form of blast furnace. It is a granulated, glassy material and has the appearance of dark coloured sand. It typically has a particle size distribution between coarse and fine sand, and a higher specific gravity than sand due to its metal content (Figure 2). The typical chemical composition of ISF slag is shown in Table 1.

**Figure 2   Zinc slag**
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Table 1  Typical chemical analysis range of ISF slag (source Britannia Zinc Ltd)

<table>
<thead>
<tr>
<th>Name</th>
<th>Composition range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron oxide</td>
<td>37-40%</td>
</tr>
<tr>
<td>Silicon dioxide</td>
<td>19-20%</td>
</tr>
<tr>
<td>Calcium oxide</td>
<td>14-16%</td>
</tr>
<tr>
<td>Zinc</td>
<td>9-12%</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>6-7%</td>
</tr>
<tr>
<td>Sulphur</td>
<td>1-3%</td>
</tr>
<tr>
<td>Lead</td>
<td>1-2%</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>1-2%</td>
</tr>
<tr>
<td>Manganese oxide</td>
<td>1%</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0-5%</td>
</tr>
<tr>
<td>Copper</td>
<td>0-5%</td>
</tr>
</tbody>
</table>

ISF slag is inherently quite stable, retaining its physical characteristics over time. However, low level leaching of metals, in particular lead, typically occurs with prolonged exposure to water.

Construction specification and related details

Specification

The activities to develop the concrete mixes for the demonstration phase focused on the requirements given in the Specification for Highway Works (SHW) [3] and the need to reflect local practice in South West England.

Common practices for the Avonmouth area (where the demonstration road was laid) include:

- Use of aggregates (typically Cheddar limestone coarse and fine aggregates with a local sea dredged Holme sand)
- Entrained air for frost resistance (target 5 to 6%)
- Workability (target slump 50-80 mm)
- Meeting 7 and 28 day strength, maximum w/c and minimum cement content requirements (target 35 N/mm² and 45-50 N/mm² respectively).

The Highways Agency SHW permits the use of a wide range of secondary aggregates in concrete road pavement construction. As indicated in the following sections, this demonstration project has shown that the ISF slag provides an aggregate with acceptable engineering properties and that concrete of good durability can be produced with ISF slag aggregates. There should be no barriers to consideration of ISF slag for inclusion in future revisions to the SHW.

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Characterisation and Development of the mixes in the laboratory

A series of laboratory concrete mixes appropriate for use in an un-reinforced concrete pavement were developed in the BRE concrete laboratory with various levels of replacement of sand by ISF slag. Details of the three laboratory concrete mixes considered for the road demonstration are shown in Table 2.

Table 2 Properties of main concrete mixes developed in BRE concrete laboratory

<table>
<thead>
<tr>
<th>Mix</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISF slag (% replacement by volume)</td>
<td>0</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>Free w/c ratio</td>
<td>0.45</td>
<td>0.45</td>
<td>0.45</td>
</tr>
<tr>
<td>Portland Cement (kg/m³) target</td>
<td>350</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Total water (kg/m³) actual</td>
<td>170</td>
<td>156</td>
<td>150</td>
</tr>
<tr>
<td>AEA (% cement)</td>
<td>0.4</td>
<td>0.21</td>
<td>0.17</td>
</tr>
<tr>
<td>WRA (% cement)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Measured Air content (%)</td>
<td>5.3</td>
<td>5.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Slump (mm)</td>
<td>60</td>
<td>70</td>
<td>65</td>
</tr>
<tr>
<td>Ease of de-moulding</td>
<td>Ok</td>
<td>Ok</td>
<td>Delayed 1 day. Fragile cube corners at 1 day.</td>
</tr>
<tr>
<td>Compressive strength (N/mm²) at 7 days (water stored)</td>
<td>38</td>
<td>41</td>
<td>40</td>
</tr>
<tr>
<td>Compressive strength (N/mm²) at 28 days (water stored)</td>
<td>46</td>
<td>50</td>
<td>49</td>
</tr>
</tbody>
</table>

The main findings were that:
- The mixes all had mix proportions, 7 day compressive strengths, and other properties that would meet the requirements of the SHW.
- Substitution of ISF slag up to 75% by volume (of sand) in the concrete did not adversely affect the 7 day strength of any mixes.
- Substitution of ISF slag at 75% by volume (of sand) did, however, produce concrete cubes with corners that were fragile at 24hrs. De-moulding of these cubes had to be delayed to 48 hours. Cubes with 0% and 50% ISF were demouldable as normal at 24 hours.

Construction process

The demonstration concrete roadway (which was laid by Hanson Premix in September 2002) included three bays made from a test concrete with ISF slag (Mix B in Table 2) and three sections of control concrete without ISF slag (Mix A in Table 2), see Figure 3. The total length was approximately 50 metres. The pavement was installed with a concrete wearing surface as this is most appropriate for monitoring the durability characteristics of the concretes in the pavement.
The ISF slag was added to the other mix constituents in the ready-mixed concrete truck with measured quantities of water being added where necessary to adjust workability. A curing membrane was sprayed on the surface of the concrete and joints were saw-cut in the surface at 24 hours. Trafficking of the roadway with a range of normal road traffic, commenced at 28 days age (Figure 4).
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Figure 4  a) Surface finishing of the concrete road  b) Concrete roadway 7 days after it was laid  c) Concrete roadway at 13 months  d) Concrete roadway at 30 months

Cost & environmental effectiveness

The quantities of these secondary materials produced may be considered small in relation to the volumes of aggregates consumed annually by the UK construction industry. However, the requirement to landfill these materials results in increased production costs and consumes valuable landfill sites. Equally, the comparatively small volumes can be readily consumed in the locality of production without affecting the local economy reliant on production of primary aggregates. This project offered an opportunity to not only demonstrate the technical feasibility of the consumption of these waste materials, but to also promote the use of small volumes of waste in construction.

Slags from primary and secondary production of zinc (such as ISF slag) are classified as hazardous waste in the European waste catalogue. Due to the reclassification of landfill sites in July 2004 as part of The Landfill (England and Wales) Regulations 2004, costs of disposal of hazardous waste are expected to rise significantly.
Evidence from this project has provided re-assurance that contaminants in the ISF slag would be effectively immobilised in the matrix of a concrete road structure in service, saving the cost of its disposal to hazardous landfill and at the same time saving £1.60/t (Aggregates Levy) for avoiding using a primary aggregate. At the end of its life, the road would be suitable for crushing to produce recycled aggregate for new construction. One remaining concern could be disposal of the road material to landfill. Assessment of the crushed concrete material (made with ISF slag) against landfill acceptance places the material in the “non-hazardous” category. Current charges for disposal of non-hazardous waste are £18/t under the landfill tax which aims to divert waste from landfill by charging for disposal. The landfill tax is expected to escalate yearly at £3/t until the charge reaches £35/t. However, it is most likely that the material would be recycled.

Performance results from assessment of the road

Properties of concrete placed on site

Concrete mixes with adequate slump, strength development and air entrainment characteristics were successfully developed and placed on site (Table 3).

<table>
<thead>
<tr>
<th></th>
<th>Control bays (no ISF)</th>
<th>Test bays (with ISF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISF slag (% replacement of sand, by volume)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Slump (mm)</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>Measured air content (%)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Compressive strength (water stored)</td>
<td>at 3 days (N/mm²)</td>
<td>35.0</td>
</tr>
<tr>
<td></td>
<td>at 7 days (N/mm²)</td>
<td>40.5</td>
</tr>
<tr>
<td></td>
<td>at 28 day (N/mm²)</td>
<td>47.5</td>
</tr>
<tr>
<td></td>
<td>at 91 days (N/mm²)</td>
<td>53.5</td>
</tr>
</tbody>
</table>

Monitoring of the concrete mixes included determination of air content and slump of the fresh mixes and compressive strength at 7 and 28 days (from cubes compacted on site without vibration). Specified levels of entrained air (5-6% for frost resistance) were achieved or exceeded and workability (target slump 50-80 mm) was slightly exceeded (up to 125 mm) in some cases but this was not considered to be significant. The compressive strength development results of the concrete bays containing ISF slag are lower than those obtained for the control bays. This is likely to be due to an extra addition of water to the ISF mix on site.
Compressive strength

The 7-day strength requirements for the concrete (>= 35 N/mm²) were met or exceeded for the control bays and one of the ISF test bays. However, the other two ISF test bays did not meet the requirement.

Initial visual assessment

Visual assessment of the six bays indicated the presence of a few minor shrinkage cracks in the ISF concrete but there was no evidence of any other problems. There was no evidence that the ISF slag adversely affected the colour of the concrete.

Cores (one per bay) were extracted by dry coring from the roadway at 6-7 days and 28 days after casting for visual assessment and leaching tests (Figure 5). A visual assessment of cores taken from the ISF and control concrete confirmed that the concrete was well compacted without any evidence of segregation. Examination of sections cut from the cores and assessed using an optical microscope indicated that the capillary porosity and voidage of the cement paste in both ISF and Control samples was higher than expected and this may affect the long term durability. There was no evidence that the ISF slag was acting as anything other than an inert constituent and there was no visible evidence of any deleterious processes.

Figure 5 Cores extracted from the concrete roadway.
Performance of the road over time

The concrete road was monitored for general condition (by visual inspection), and carbonation and chloride ingress at approximately one year (October 2003) and again after 30 months where a more detailed inspection and laboratory assessment was undertaken.

Visual observations of the road after one year and 30 months revealed that the ISF containing bays were behaving as well as or better than the control bays. Cracks were observed on the control bays, but were believed to be due more to the poor surface finish than to the quality of the concrete. The ISF containing bays showed the presence of one very long, fine crack, on one of the bays. This crack was believed to be due to the sawn joints not being cut deep enough.

The carbonation depth of both the control mix and the ISF slag mix after 13 months and 30 months was approx. 2 mm. There was evidence of slight chloride ingress (from de-icing salts) on both the ISF slag and the control mixes. The maximum amount of chloride by mass of cement on both mixes was approx 0.2% at both test ages and was similar in both the conventional test and ISF concretes. This level of chloride would not give cause for concern for reinforcement corrosion, if reinforcement were present in this case.

Results of laboratory work on mixes used for road

Laboratory assessment tests

A full programme of laboratory assessment tests (initiated after the demonstration phase) was undertaken on two laboratory concrete mixes developed to be as identical as possible to those used for the roadways. These tests include mechanical tests on the hardened concrete and assessment of the fresh concrete. Monitoring continued at intervals to 91 days (depending on test type). Tests results are described in Table 4 and are presented in the WRAP technical report for this project [2].

Table 4  Laboratory testing programme for the concrete mixes containing ISF slag, compared with the control mix

<table>
<thead>
<tr>
<th>Test</th>
<th>Results/ comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cube strength development from 1 day to 3 months age. (BS EN 12390-2:2000)</td>
<td>the ISF slag concrete had slightly higher compressive strength than the control concrete. The improvement in the compressive strength became more pronounced with time. (43 N/mm$^2$ for control mix and 51 N/mm$^2$ for ISF mix at 28 days age)</td>
</tr>
<tr>
<td>Flexural strength @ 28 days age. (BS EN 12390-5:2000)</td>
<td>the ISF mix concrete had a higher flexural strength than the control mix. (5.7 N/mm$^2$ for control mix and 6.4 N/mm$^2$ for the ISF mix at 28 days age)</td>
</tr>
</tbody>
</table>
Leach testing

It was considered impractical to undertake meaningful in-situ leach tests on the trial road sections due to the potential for high levels of contamination at the BZL site. Assessment of leaching therefore focused on leach testing in the laboratory of the concrete used in the road sections.

Leach testing on cores / cubes

Leach testing (using the draft method developed by CEN/TC292/WG2 [4] for leaching of monolithic wastes) on cores (from the demonstration concrete roadway) and site-compacted cubes at 7 days age, showed the following results:

- Levels of all metals were all below the limits for inert landfill and were similar for control and ISF samples
- Levels of lead (Pb) were below the detection limits in both control and ISF samples (equiv to 0.004 mg/kg)
- Levels of arsenic (As) leached from all specimens were negligible and were similar for control and ISF samples
- Levels of zinc (Zn) were highest for ISF core sample. Levels leached from cubes were negligible and were similar for control and ISF samples

Leach testing of crushed material

One potential concern with concretes made with secondary aggregates can be the potential for leaching when the concrete is crushed and recycled. This was addressed by assessing leachability from crushed material.

Concrete cubes made from the demonstration phase concretes (ISF and control concrete) have been crushed and duplicate samples sent for Leachate Availability Test (LAT) compliance test to BSEN 12457-3:2002 [5]. Results are as follows:

- The amounts of zinc and arsenic leached from the ISF concrete were comparable to those from the control mixes.
- The amount of lead leached from the crushed ISF concrete is greater than that leached from the unbound ISF slag itself. This is due to the enhanced solubility of lead under alkaline conditions. However, this situation is expected to improve as the concrete in the road ages and becomes less alkaline.

Slags from primary and secondary production of zinc (such as ISF slag) are classified as hazardous waste in the European waste catalogue. This means that leaching test evidence would need to be presented to the Environment Agency (EA) before their wider adoption as aggregates and any exemptions from waste management requirements could be considered on a local basis. Exemptions from waste management regulations are likely to be more
difficult to achieve than for accepted materials such as air cooled blastfurnace slag or steel slag.

**Environmental/ regulatory issues**

Laboratory leach testing of high quality ISF slag concrete with landfill acceptance tests has provided evidence that contaminants within the ISF slag are effectively bound up when the slag is used as an aggregate in concrete. Furthermore, a properly designed and constructed road will in fact minimise water ingress and percolation through its structure. Both these facts provide re-assurance that contaminants in the ISF slag would be effectively immobilised in the matrix of a concrete road structure in service.

At the end of its life, the road would be suitable for crushing to produce recycled aggregate for new construction. One remaining concern could be disposal of the road material to landfill. Assessment of the crushed concrete material (made with ISF slag) against landfill acceptance criteria for granular waste has indicated that levels of lead leached from crushed concrete containing ISF slag exceeds the limits for inert waste. However, it is most likely that in fact the road material would be recycled.

**Conclusions**

The objectives of the project were to:

- develop mix designs for concrete containing ISF slag from zinc production
- demonstrate the use of the ferro-silicate slag through the construction of demonstration road sections.

These objectives have been met to a high degree. Concrete mixes containing ISF slag aggregate have been successfully made and the planned roadway has been placed and assessed. The project has successfully demonstrated the feasibility of using ISF slag as a partial replacement for sand (up to 50% by volume) in pavement quality concrete.
References

3. Highways Agency Specification for Highway Works Vol 1, Series 1000 (SHW)
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