



**CCSP Deliverable D544
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D544 Carbonation of residual slag



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Treatment of Steel Slag Residues using Accelerated Carbonation

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Treatment of Steel Slag Residues using Accelerated Carbonation

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1. Introduction

This report summarises the laboratory investigations to produce an aggregate product from steel slag residues provided by Tapojärvi.

2. Materials and Methods

A sample of raw steel slag was provided by Tapojärvi (our ref: C8S540).

2.1 Material Preparation

In addition to evaluating the raw slag, the residual slag obtained after washing with ammonium chloride was also studied.

The residual slag was prepared in the laboratory as follows:

- Prepare 2M NH_4Cl and record the pH of the solution (a rise pH will be an indication that extraction takes place).
- Pour the solution into a large beaker containing a magnetic stirring rod
- Add the slag to the solution (solid-to-liquid ratio of 0.1)
- Place the beaker on a magnetic stirrer unit
- Measure the pH after 2 h. If it is under 9, continue for another 2 h. Write down the final pH (can't recall the exact pH for this concentration, but it should be around 9-10)
- Filter the slurry using vacuum filtration
- Wash the filtered slurry with water
- Oven dry the filtered solid

Samples of residual slag and filtrate were sent to Tapojärvi and VTT, respectively, for analysis.

The intermediate products generated by the washing procedure (i.e. the steel slag after initial filtering, and after washing with water) were considered for use in the carbonation experiments. However, the ammonia smell from the filtered solid was so strong, that working with it was deemed unsafe, and indeed would be very difficult to process on an industrial scale. The water-washed material was also not trialled as it would have to be partially dried anyway to achieve the required moisture content for processing.

2.2 Carbonation Testing

The steel slag was tested for its reactivity with carbon dioxide in a pressurised reaction vessel (operating at 2 bar). As a waste material reacts with carbon dioxide, its mass increases and a simple gravimetric method can be employed to determine its reactivity (to CO_2) by measuring its mass before and after the reaction. The materials were kept in the pressure vessel for 24 hours.

2.3 Aggregate Product Development

Trials were carried out to determine if an aggregate product with potential for re-use could be manufactured from the steel slag. Table 1 shows the formulations used.

Table 1: Formulations trialled

ID	Material	Filler	Binder	Curing
M1	Raw Steel Slag	20%	-	Air
M2	Raw Steel Slag	20%	10% CEM1	Air
M3	Raw Steel Slag	20%	20% CEM1	Air
M4	Steel Slag residue	20%	-	Air
M5	Steel Slag residue	20%	10% CEM1	Air
M6	Steel Slag residue	20%	20% CEM1	Air
M7	Raw Steel Slag	20%	-	CO ₂
M8	Raw Steel Slag	20%	10% CEM1	CO ₂
M9	Raw Steel Slag	20%	20% CEM1	CO ₂
M10	Steel Slag residue	20%	-	CO ₂
M11	Steel Slag residue	20%	10% CEM1	CO ₂
M12	Steel Slag residue	20%	20% CEM1	CO ₂

Pelletised aggregates were formed and placed in 2 different curing environments for three days to observe rates of hardening. The curing environments were

- 100% pure carbon dioxide
- Air

The compressive strength of individual aggregates was determined using a single particle crushing method. The pellets were also tested for contaminant mobility using a water-leaching test (BS EN 12457-2) followed by analysis of the leachate by ICP-OES (Perkin Elmer Optima 4300DV).

The results were compared to a standard specification used by Carbon8.

3. Results

3.1 Properties of the Materials

Analysis of the leachates from the materials are shown in table 2. The analytes are those set out in the Waste Acceptance Criteria (WAC) for wastes sent to landfill. The results indicated that the contaminants of concern were barium, chromium, and molybdenum in the raw slag. In the slag residue, only was significant.

Table 5: Leaching behaviour (values in mg/kg)

	Raw Steel Slag	Residual Steel Slag	Inert WAC Limit	Stable Non-Reactive WAC Limit	Hazardous WAC Limit
Antimony	<0.06	<0.06	0.06	0.7	5
Arsenic	<0.18	<0.18	0.5	2	25
Barium	15.81	0.43	20	100	300
Cadmium	<0.02	<0.02	0.04	1	5
Chromium	1.50	1.70	0.5	10	70
Copper	<0.10	<0.10	2	50	100
Lead	<0.13	<0.13	0.5	10	50
Molybdenum	2.43	<0.02	0.01	0.2	2
Nickel	<0.14	<0.14	0.5	10	30
Selenium	<0.10	<0.10	0.4	10	40
Zinc	<0.20	<0.20	0.1	0.5	7
Chloride	<3,030	<3,030	4	50	200
Sulfate	<11	<11	800	15,000	25,000

3.2 Carbonation

CO₂ uptakes from the samples are shown in table 3. The uptake of the raw slag was 9.6%, which was reduced to 5.2% in the residual slag. The decrease may be ascribed to the removal of reactive calcium during the washing process.

Table 3: CO₂ Uptake

Material	CO ₂ Uptake (%)
Raw steel slag	9.6
Residual steel slag	5.2

3.3 Properties of the Aggregate

An example of pellets produced from steel slag is shown in figure 1. The aggregate has been tested according to a standard QA protocol developed by Carbon8, including compressive strength (see figures 2 and 3).

The raw slag and slag residue on their own did not produce pellets that achieved the target strength. Therefore, a cement binder was added. With the addition of 10% CEM1, the target strength (0.1 MPa) was achieved at 3 days. With 20% CEM1 addition, this was achieved between 1 and 2 days.

Compared to curing in air, no strength enhancement was achieved by curing in a CO₂ environment.

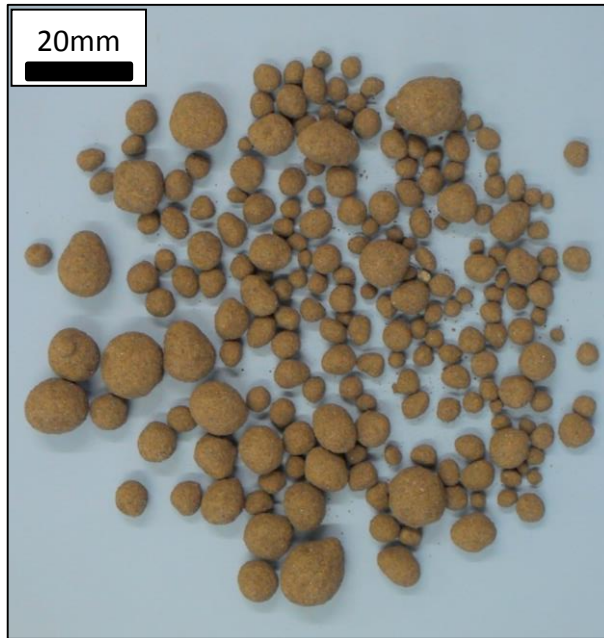


Figure 3: Carbonated steel slag pellets

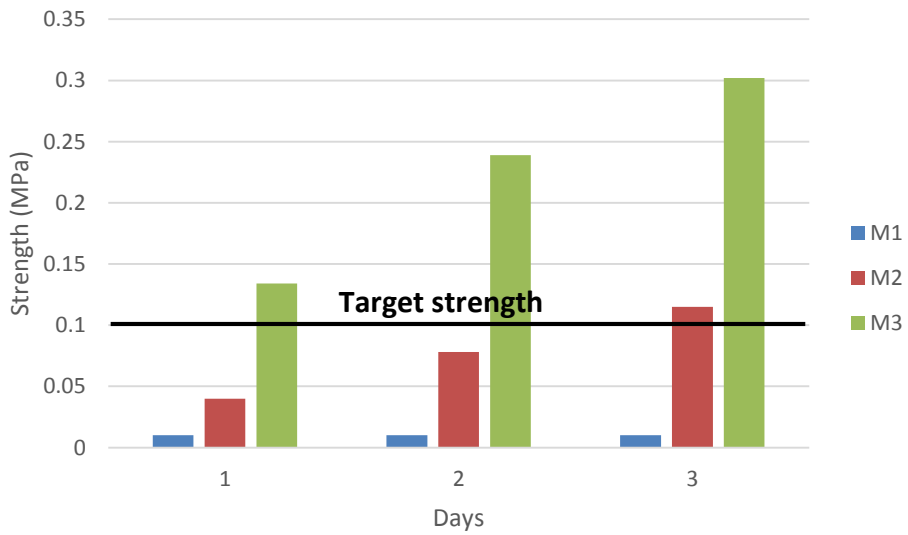


Figure 2a: Compressive strength of air cured products

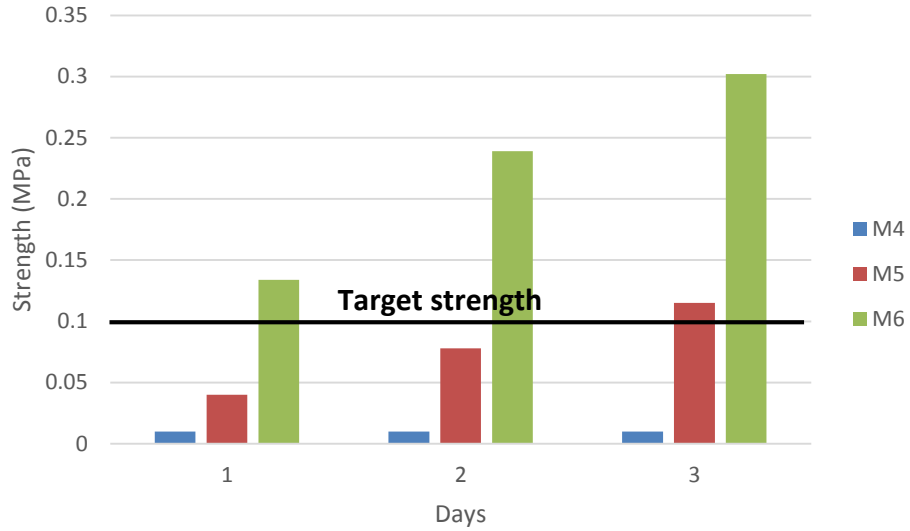


Figure 2b: Compressive strength of air cured products

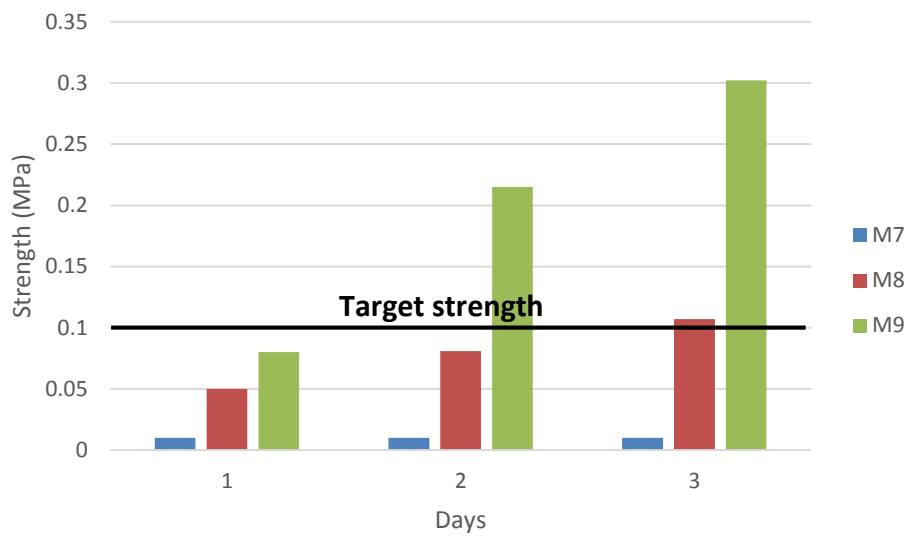


Figure 3a: Compressive strength of CO₂ cured products

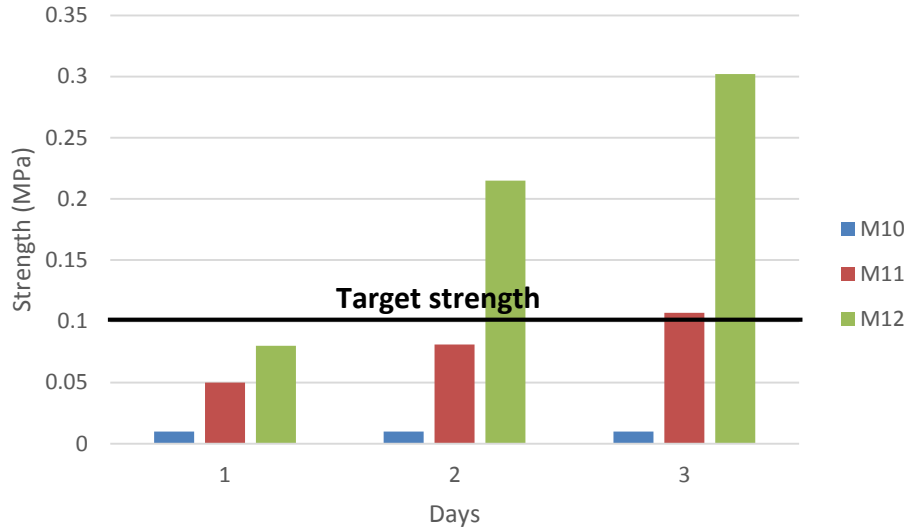


Figure 3b: Compressive strength of CO₂ cured products

Leaching results for the aggregates are shown in tables 4 and 5. For the air cured aggregate, chromium and molybdenum remained as issues. When cured in CO₂, all materials met the C8 specification.

Table 4: Leaching behaviour of the air cured aggregate (values in mg/kg)

	M1	M2	M3	M4	M5	M6	C8 Spec
Antimony	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	0.06
Arsenic	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	0.5
Barium	10.86	8.55	6.12	<0.20	<0.20	<0.20	50
Cadmium	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.04
Chromium	1.93	0.94	0.70	2.50	2.42	2.34	1.5
Copper	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	0.15
Lead	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	0.5
Molybdenum	1.86	1.33	0.92	<0.02	0.48	0.33	1.0
Nickel	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	0.4
Selenium	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.1
Zinc	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	3.5
Chloride	<3,030	<3,030	<3,030	<3,030	<3,030	<3,030	75,000
Sulfate	<11	<11	<11	<11	<11	<11	5,000

Values in red exceed the C8 specification

Table 5: Leaching behaviour of the CO₂ cured aggregate (values in mg/kg)

	M7	M8	M9	M10	M11	M12	C8 Spec
Antimony	<0.06	<0.06	<0.06	<0.06	<0.06	<0.06	0.06
Arsenic	<0.18	<0.18	<0.18	<0.18	<0.18	<0.18	0.5
Barium	0.23	<0.20	<0.20	<0.20	<0.20	<0.20	50
Cadmium	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	0.04
Chromium	<0.10	<0.10	<0.10	<0.10	0.47	<0.10	1.5
Copper	<0.04	<0.04	<0.04	<0.04	<0.04	<0.04	0.15
Lead	<0.13	<0.13	<0.13	<0.13	<0.13	<0.13	0.5
Molybdenum	<0.02	<0.02	<0.02	<0.02	0.37	<0.02	1.0
Nickel	<0.14	<0.14	<0.14	<0.14	<0.14	<0.14	0.4
Selenium	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.1
Zinc	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20	3.5
Chloride	<3,030	<3,030	<3,030	<3,030	<3,030	<3,030	75,000
Sulfate	<11	<11	<11	<11	<11	<11	5,000

4. Summary

The findings of this investigation are summarised as:

- A sample of raw steel slag was supplied by Tapojärvi
- Steel slag residue was prepared at the University of Greenwich, and supplied to Tapojärvi for testing
- Leaching analysis revealed barium, chromium, and molybdenum as contaminants of concern in the raw slag. Only remained as a problem in the slag residue
- Both materials were found to be reactive with carbon dioxide. The uptake of the slag residue was lower, presumably due to removal of reactive calcium
- Aggregate was prepared from both materials, with and without added binder. The aggregate was cured in both air, and in a pure CO₂ environment
- Curing in CO₂ reduced the leaching of chromium and molybdenum, which remained an issue in the un-carbonated aggregate, although did not improve strength development.