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# **The environmental impact evaluation and testing of sustainable inorganic binders: A green alternative to ordinary Portland cement**

**by**

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# CONTENT

A wide-angle photograph of the Antalya International University building. The building is a large, modern structure with a central archway and multiple wings. The sky is blue with some clouds. In the foreground, there is a paved area and some greenery.

- INTRODUCTION

- AIM

- MATERIALS

- METHODOLOGY

- RESULTS and  
CONCLUSIONS

# INTRODUCTION

- ▶ Main debate is...
- ▶ Concrete or Steel?
- ▶ If concrete, why? If not, why?
- ▶ If Steel, why? If not, why?



# Material selection

**is all based on:**

- ▶ Type of application,
- ▶ Economic concerns,
- ▶ Architectural and
- ▶ Functional concerns and issues related to sustainability





# CONCRETE

- ▶ More resistant to very high temperatures for longer period of time
- ▶ Offer excellent protection from explosions
  - For example: Burj Khalifa, Dubai – a very good example for concrete base buildings where around 330,000 cubic meters of concrete used to complete its construction (of course supported by steel rebar).
- ▶ Speeds up the construction process by giving the ability to be pre-fabricated off site unlike to Steel



# STEEL

- ▶ Can be a more environmental friendly option compared to concrete due to concrete's high carbon emissions during its production process
- ▶ Steel is a recyclable materials and currently reinforced steel is the most preferred material to protect environment
- ▶ Rebar is mosly made up 100% recycled scrap Steel and at the end of its life cycle it can be recovered, recycled and used again where concrete CANNOT do that at this high levels and with 100% efficiency.
- ▶ Steel offers aesthetics that concrete may never be able to.



# Steel vs. Concrete!

- ▶ In reality, both concrete and Steel have advantages and disadvantages so why we should choose one over another where it would be possible to apply them together.
- ▶ Reinforcing concrete with Steel has major benefits. It is by far a lot better than either concrete or Steel by their own.
- ▶



# So!....

- ▶ How can we make a more environmental friendly and stronger material with higher durability, less production costs and maintenance cost. ?
- ▶ What about producing green concrete which is basically rely on green cement? What about producing a green reinforcing concrete?
- ▶ In the light of discussion we have started to think about more sustainable construction materials which can reduce the detrimental impacts of cement whereas carries similar or better characteristics which will not effect the quality, durability and cost of the final product or buildings.





# AIM

- ▶ To reduce the cement content in reinforced concrete by using sustainable alternative binding agents.



# MATERIALS

- ▶ Sustainable construction materials should not only be environmental friendly but also provide high level of safety and cost effectiveness over the long term.
- ▶ Low grade magnesium oxide (LGMgO),
- ▶ pulverised fuel ash (PFA),
- ▶ Steel slag and
- ▶ hydrated lime
  - are the materials proposed as a cement replacement.



# METHODOLOGY

- ▶ Setting Time
- ▶ Unconfined Compressive Strength (UCS)
- ▶ Leaching Tests (Monolithic and Granular)
- ▶ Acid Neutralisation Capacity (ANC)
- ▶ Diffusion Test
- ▶ SEM
- ▶ XRD analyses
- ▶ And many others....



# RESULTS



# Cement-binder substitution ratios

| Mix             | CEMI (%) | Binder (%) |
|-----------------|----------|------------|
| CEMI-BINDER-1:1 | 50       | 50         |
| CEMI-BINDER-1:2 | 33       | 67         |
| CEMI-BINDER-1:3 | 25       | 75         |
| CEMI-BINDER-1:4 | 20       | 80         |
| CEMI-BINDER-1:5 | 17       | 83         |
| CEMI-BINDER-1:6 | 14       | 86         |
| CEMI-BINDER-1:7 | 12.5     | 87.5       |
| CEMI-BINDER-1:8 | 11       | 89         |
| CEMI-BINDER-1:9 | 10       | 90         |

\*Binder = Slag / LGMgO / PFA / hlime

|                   |     |     |     |     |     |     |     |     |     |
|-------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| <b>CEMI-hlime</b> | 1:1 | 1:2 | 1:3 | 1:4 | 1:5 | 1:6 | 1:7 | 1:8 | 1:9 |
| <b>Water (%)</b>  | 60  | 60  | 60  | 60  | 60  | 60  | 60  | 60  | 60  |
| <b>CEMI-LGMgO</b> | 1:1 | 1:2 | 1:3 | 1:4 | 1:5 | 1:6 | 1:7 | 1:8 | 1:9 |
| <b>Water (%)</b>  | 40  | 40  | 45  | 45  | 50  | 50  | 50  | 50  | 50  |
| <b>CEMI-PFA</b>   | 1:1 | 1:2 | 1:3 | 1:4 | 1:5 | 1:6 | 1:7 | 1:8 | 1:9 |
| <b>Water (%)</b>  | 20  | 20  | 20  | 20  | 20  | 20  | 20  | 20  | 20  |
| <b>CEMI-SLAG</b>  | 1:1 | 1:2 | 1:3 | 1:4 | 1:5 | 1:6 | 1:7 | 1:8 | 1:9 |
| <b>Water (%)</b>  | 18  | 15  | 15  | 15  | 18  | 15  | 15  | 15  | 15  |





# UCS RESULTS



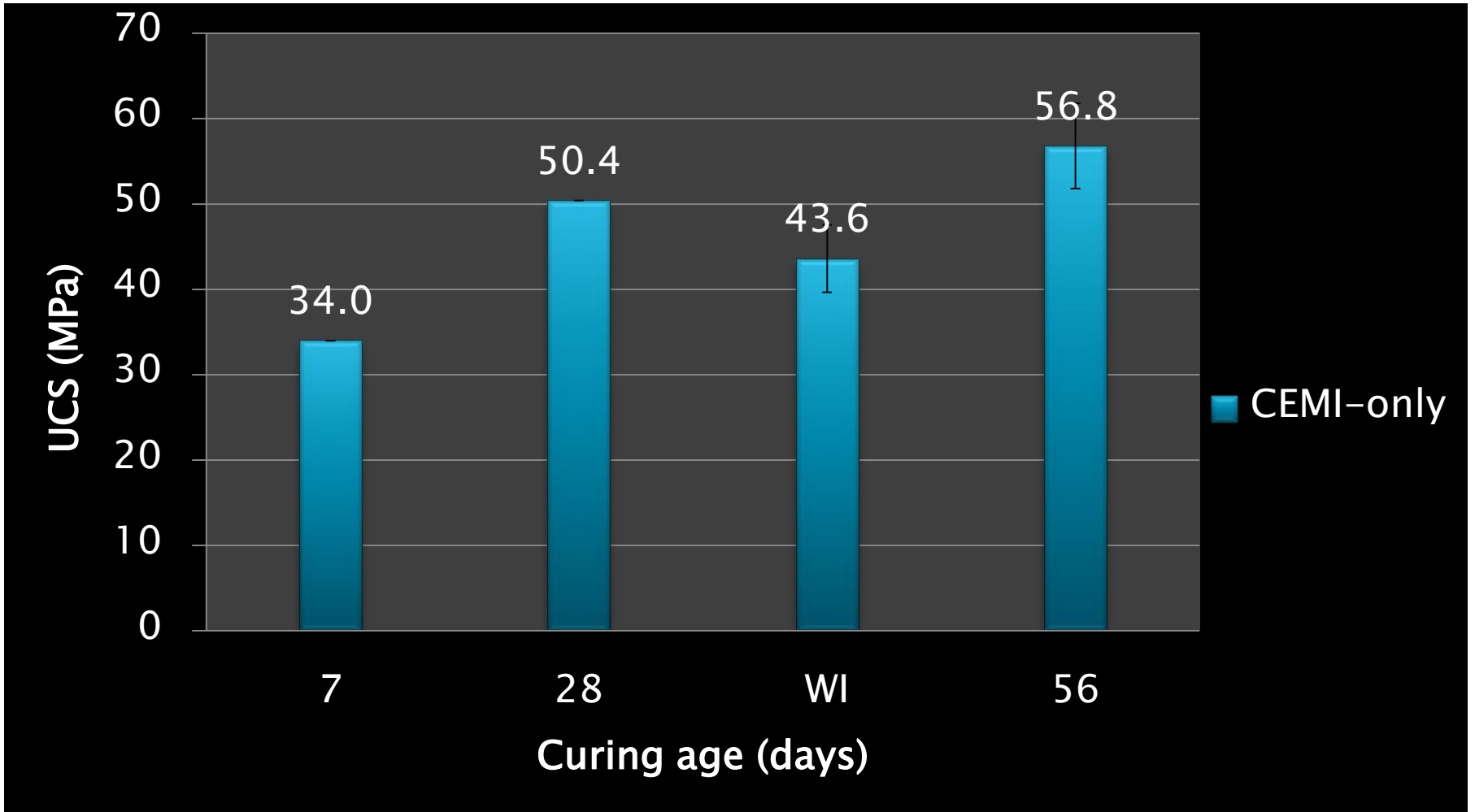
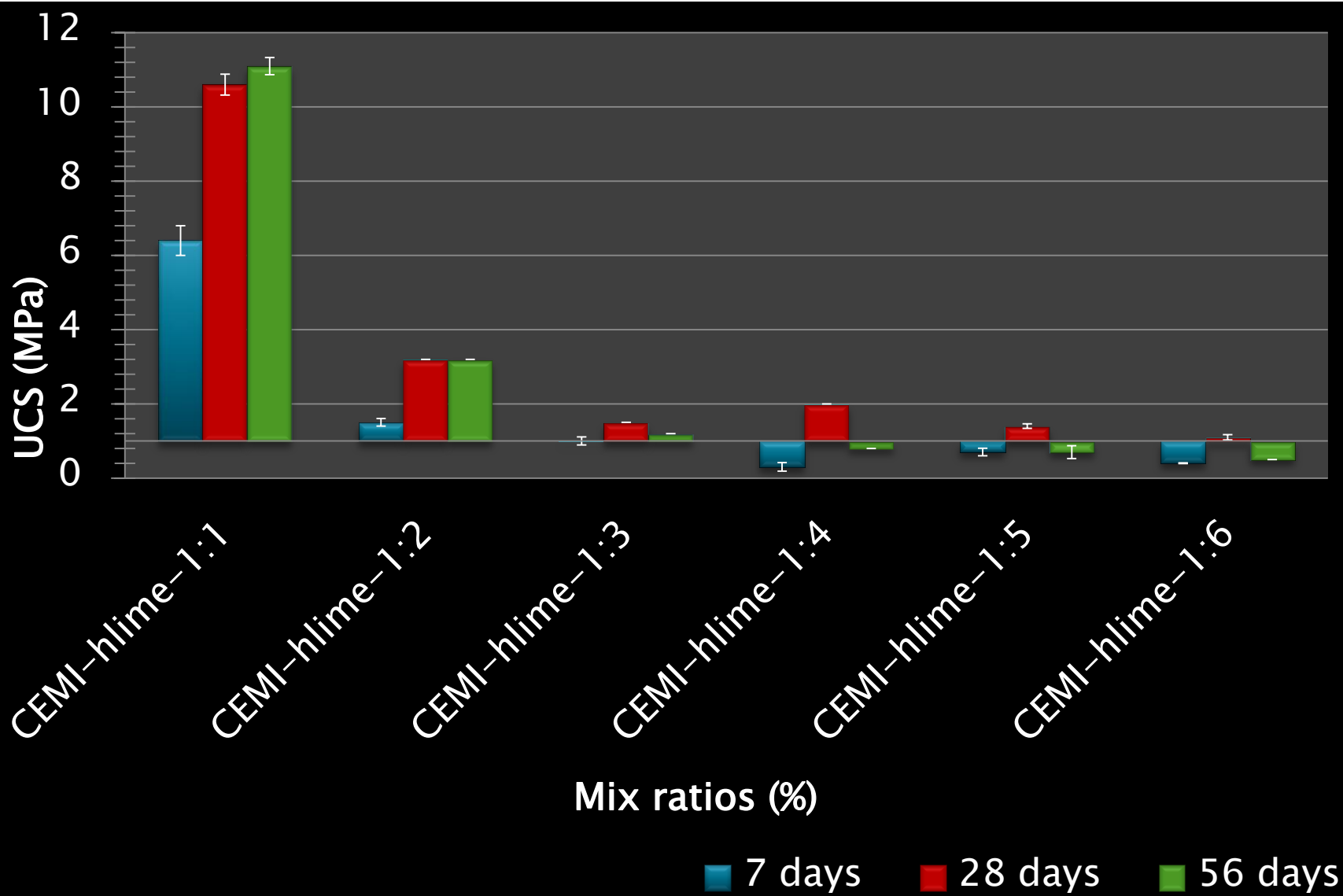


Figure 1 CEMI-only mix combinations for UCS 7, 28, 56 days and WI (28 days)

*\*Error bars with standard deviations included*





**Figure 2 CEMI-hlime mix combinations for UCS 7, 28 and 56 days**

*\*Error bars with standard deviations included*

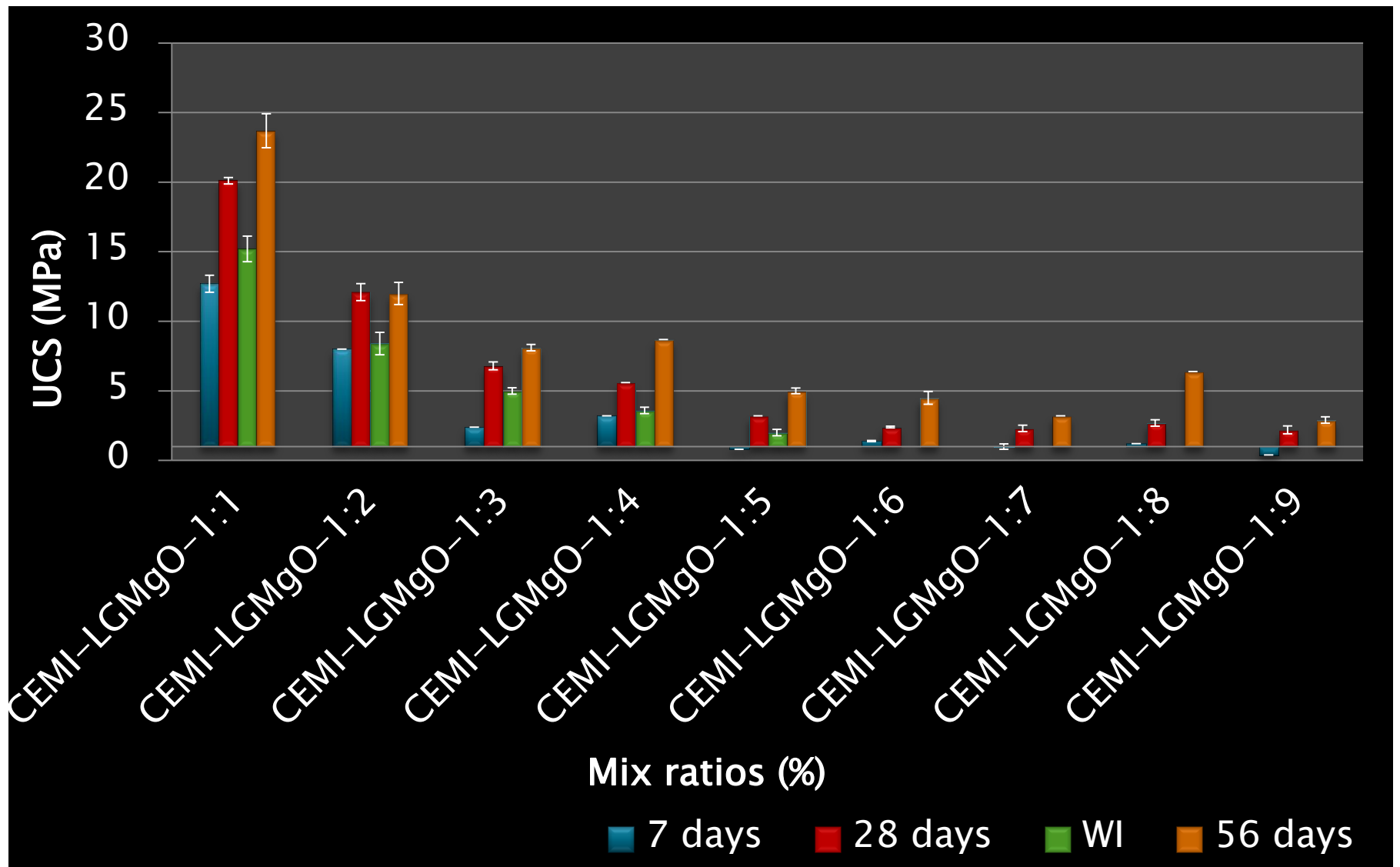
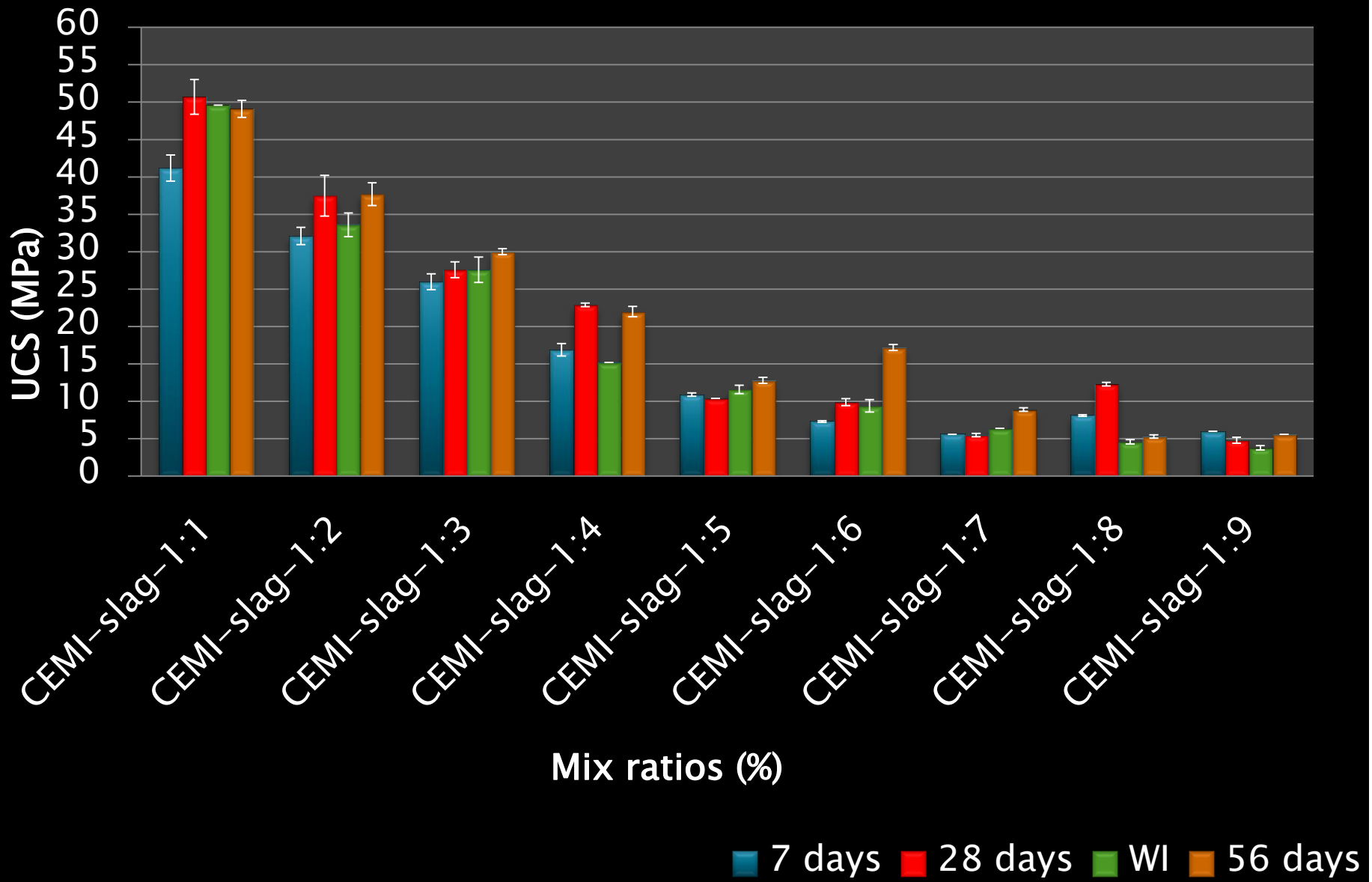


Figure 3 CEMI-LGMgO mix combinations for UCS 7, 28, and 56 days and WI (28 days)

*\*Error bars with standard deviations included*





**CEMI-slag mix combinations for UCS 7, 28, and 56 days, WI (28 days)**

*\*Error bars with standard deviations included*



Table 1 CEMI-hlime mix combinations for UCS WI, 180 and 630 days

| Mix            | Curing period (days)<br>UCS values (MPa) |       |       |           |
|----------------|------------------------------------------|-------|-------|-----------|
|                | WI                                       | 180 d | 630 d | w/s ratio |
| CEMI-hlime-1:1 | 10.9                                     | NA    | 11.8  | 0.6       |
| CEMI-hlime-1:2 | 3.4                                      | NA    | NA    | 0.6       |
| CEMI-hlime-1:3 | NA                                       | 1.6   | NA    | 0.6       |
| CEMI-hlime-1:4 | NA                                       | 0.4   | 0.4   | 0.6       |
| CEMI-hlime-1:5 | NA                                       | 0.1   | 0.3   | 0.6       |
| CEMI-hlime-1:6 | NA                                       | 0.1   | 0.1   | 0.6       |

Table 3 CEMI-PFA mix combinations for UCS 90 days and WI

| Mix          | Curing period (days)<br>UCS values (MPa) |      |           |
|--------------|------------------------------------------|------|-----------|
|              | WI                                       | 90 d | w/s ratio |
| CEMI-PFA-1:1 | 42.0                                     | 36.4 | 0.20      |
| CEMI-PFA-1:2 | 27.8                                     | NA   | 0.20      |
| CEMI-PFA-1:3 | NA                                       | NA   | 0.20      |
| CEMI-PFA-1:4 | NA                                       | NA   | 0.20      |
| CEMI-PFA-1:5 | NA                                       | NA   | 0.20      |
| CEMI-PFA-1:6 | NA                                       | NA   | 0.20      |
| CEMI-PFA-1:7 | 9.2                                      | 12.3 | 0.20      |
| CEMI-PFA-1:8 | 9.2                                      | 11.6 | 0.20      |
| CEMI-PFA-1:9 | 7.6                                      | NA   | 0.20      |

Table 2 CEMI-LGMgO mix combinations for UCS 70 and 180 days

| Mix            | Curing period (days)<br>UCS values (MPa) |       |           |
|----------------|------------------------------------------|-------|-----------|
|                | 70 d                                     | 180 d | w/s ratio |
| CEMI-LGMgO-1:1 | 22.4                                     | NA    | 0.40      |
| CEMI-LGMgO-1:2 | 16.8                                     | NA    | 0.40      |
| CEMI-LGMgO-1:3 | 10.1                                     | NA    | 0.45      |
| CEMI-LGMgO-1:4 | 3.9                                      | NA    | 0.45      |
| CEMI-LGMgO-1:5 | 2.4                                      | NA    | 0.50      |
| CEMI-LGMgO-1:6 | 2.4                                      | 3.0   | 0.50      |
| CEMI-LGMgO-1:7 | NA                                       | 3.8   | 0.50      |
| CEMI-LGMgO-1:8 | 3.6                                      | 3.6   | 0.50      |
| CEMI-LGMgO-1:9 | 3.6                                      | 3.0   | 0.50      |

Table 4 CEMI-slag mix combinations for UCS 70 and 120 days

| Mix           | Curing period (days)<br>UCS values (MPa) |      |           |
|---------------|------------------------------------------|------|-----------|
|               | 70 d                                     | 120d | w/s ratio |
| CEMI-slag-1:1 | NA                                       | NA   | 0.18      |
| CEMI-slag-1:2 | 46.4                                     | NA   | 0.15      |
| CEMI-slag-1:3 | NA                                       | NA   | 0.15      |
| CEMI-slag-1:4 | 32.5                                     | NA   | 0.15      |
| CEMI-slag-1:5 | 20.4                                     | 13.6 | 0.15      |
| CEMI-slag-1:6 | 22.0                                     | NA   | 0.15      |
| CEMI-slag-1:7 | NA                                       | 8.4  | 0.15      |
| CEMI-slag-1:8 | NA                                       | NA   | 0.15      |
| CEMI-slag-1:9 | NA                                       | NA   | 0.15      |

# Leaching Test Results



# Leaching Test Results – Granular Leaching Test

| CEMI:hlime ratio | Pb mg/l   | Cd mg/l   | Cr mg/l   | Zn mg/l   | Mo mg/l   | As mg/l   | Pb limit | Pb   | Cd limit | Cd  | Cr limit | Cr   | Zn limit | Zn  | Mo limit | Mo    | As limit | As  |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|----------|------|----------|-----|----------|------|----------|-----|----------|-------|----------|-----|
| 1:1              | BDL       | BDL       | 0.07      | BDL       | 0.04      | BDL       | 50       | BDL  | 5        | BDL | 70       | 0.7  | 200      | BDL | 30       | 0.42  | 25       | BDL |
| 1:2              |           |           | 0.07      |           | BDL       |           |          |      |          |     |          | 0.69 |          |     |          | BDL   |          |     |
| 1:3              |           |           | 0.08      |           | 0.01      |           |          |      |          |     |          | 0.8  |          |     |          | 0.14  |          |     |
| 1:4              |           |           | 0.07      |           | BDL       |           |          |      |          |     |          | 0.7  |          |     |          | BDL   |          |     |
| 1:5              |           |           | 0.06      |           | 0.02      |           |          |      |          |     |          | 0.67 |          |     |          | 0.16  |          |     |
| 1:6              |           |           | 0.07      |           | 0.01      |           |          |      |          |     |          | 0.67 |          |     |          | 0.13  |          |     |
| CEMI:hlime ratio | Co (mg/l) | Cu (mg/l) | Ni (mg/l) | Se (mg/l) | Ba (mg/l) | Sb (mg/l) | Co limit | Co   | Cu limit | Cu  | Ni limit | Ni   | Se limit | Se  | Ba limit | Ba    | Sb limit | Sb  |
| 1:1              | 0.01      | BDL       | 0.02      | BDL       | 1.60      | BDL       | na       | 0.13 | 100      | BDL | 40       | 0.17 | 7        | BDL | 300      | 15.95 | 5        | BDL |
| 1:2              | 0.01      |           | 0.02      |           | 1.49      |           |          | 0.10 |          |     |          | 0.15 |          |     |          | 14.87 |          |     |
| 1:3              | BDL       |           | 0.02      |           | 1.85      |           |          | BDL  |          |     |          | 0.16 |          |     |          | 18.53 |          |     |
| 1:4              | 0.01      |           | 0.02      |           | 1.65      |           |          | 0.12 |          |     |          | 0.17 |          |     |          | 16.46 |          |     |
| 1:5              | 0.01      |           | 0.02      |           | 1.71      |           |          | 0.12 |          |     |          | 0.14 |          |     |          | 17.11 |          |     |
| 1:6              | 0.01      |           | 0.02      |           | 2.09      |           |          | 0.12 |          |     |          | 0.17 |          |     |          | 20.85 |          |     |

\*The WAC limits are highlighted in yellow

\*\*BDL stands for Below Detection Limit

# Granular Leaching Test Results

| CEMI:LGMg<br>O ratio | Pb<br>(mg/l) | Cd<br>(mg/l) | Cr<br>(mg/l) | Zn<br>(mg/l) | Mo<br>(mg/l) | As<br>(mg/l) | Pb<br>limi<br>t | Pb   | Cd<br>limi<br>t | Cd  | Cr<br>limi<br>t | Cr           | Zn<br>limi<br>t | Zn  | Mo<br>limi<br>t | Mo   | As<br>limi<br>t | As  |              |
|----------------------|--------------|--------------|--------------|--------------|--------------|--------------|-----------------|------|-----------------|-----|-----------------|--------------|-----------------|-----|-----------------|------|-----------------|-----|--------------|
| 1:1                  | BDL          | BDL          | 0.04         | BDL          | BDL          | BDL          | 50              | BDL  | 5               | BDL | 70              | 0.43         | 200             | BDL | 30              | BDL  | 25              | BDL |              |
| 1:2                  |              |              | 0.06         |              |              |              |                 |      |                 |     |                 | 0.58         |                 |     |                 | 0.03 |                 |     |              |
| 1:3                  |              |              | 0.05         |              |              |              |                 |      |                 |     |                 | 0.50         |                 |     |                 | 0.02 |                 |     |              |
| 1:4                  |              |              | 0.05         |              |              |              |                 |      |                 |     |                 | 0.52         |                 |     |                 | BDL  |                 |     |              |
| 1:5                  |              |              | 0.04         |              |              |              |                 |      |                 |     |                 | 0.44         |                 |     |                 |      |                 |     |              |
| 1:6                  |              |              | 0.05         |              |              |              |                 |      |                 |     |                 | 0.47         |                 |     |                 |      |                 |     |              |
| 1:7                  |              |              | 0.04         |              |              |              |                 |      |                 |     |                 | 0.42         |                 |     |                 |      |                 |     |              |
| 1:8                  |              |              | 0.03         |              |              |              |                 |      |                 |     |                 | 0.31         |                 |     |                 |      |                 |     |              |
| 1:9                  |              |              | 0.04         |              |              |              |                 |      |                 |     |                 | 0.35         |                 |     |                 |      |                 |     |              |
| CEMI:LGMg<br>O ratio |              |              | Co<br>(mg/l) |              |              |              |                 |      |                 |     |                 | Cu<br>(mg/l) |                 |     |                 |      |                 |     | Ni<br>(mg/l) |
| 1:1                  | BDL          | BDL          | 0.01         | BDL          | 1.03         | BDL          | na              | BDL  | 100             | BDL | 40              | 0.13         | 7               | BDL | 300             |      | 10.26           | 5   | BDL          |
| 1:2                  | 0.01         |              | 0.02         |              | 0.42         |              |                 | 0.13 |                 |     |                 | 0.16         |                 |     |                 |      | 4.18            |     |              |
| 1:3                  | 0.01         |              | 0.02         |              | 0.49         |              |                 | 0.13 |                 |     |                 | 0.16         |                 |     |                 | 4.86 |                 |     |              |
| 1:4                  | 0.01         |              | 0.02         |              | 0.11         |              |                 | 0.13 |                 |     |                 | 0.16         |                 |     |                 | 1.06 |                 |     |              |
| 1:5                  | BDL          |              | 0.01         |              | 0.06         |              |                 | BDL  |                 |     |                 | 0.13         |                 |     |                 | 0.62 |                 |     |              |
| 1:6                  |              |              | BDL          |              | BDL          |              |                 | BDL  |                 |     |                 | BDL          |                 |     |                 | 0.09 |                 |     |              |
| 1:7                  |              |              | 0.02         |              | 0.05         |              |                 |      |                 |     |                 | 0.15         |                 |     |                 | 0.51 |                 |     |              |
| 1:8                  |              |              | 0.02         |              | 0.03         |              |                 |      |                 |     |                 | 0.17         |                 |     |                 | 0.32 |                 |     |              |
| 1:9                  |              |              | 0.02         |              | 0.01         |              |                 |      |                 |     |                 | 0.16         |                 |     |                 | 0.11 |                 |     |              |

# Granular Leaching Test Results

| CEMI:PFA ratio | Pb (mg/l) | Cd mg/l   | Cr (mg/l) | Zn (mg/l) | Mo (mg/l) | As (mg/l) | Pb limit | Pb   | Cd limit | Cd   | Cr limit | Cr   | Zn limit | Zn  | Mo limit | Mo    | As limit | As  |      |
|----------------|-----------|-----------|-----------|-----------|-----------|-----------|----------|------|----------|------|----------|------|----------|-----|----------|-------|----------|-----|------|
| 1:1            | BDL       | BDL       | 0.04      | BDL       | 0.19      | BDL       | 50       | BDL  | 5        | BDL  | 70       | 0.40 | 200      | BDL | 30       | 1.9   | 25       | BDL |      |
| 1:2            |           |           | 0.06      |           | 0.20      |           |          |      |          |      |          | 0.58 |          |     |          | 2.0   |          |     |      |
| 1:3            |           |           | 0.18      |           | 0.19      |           |          |      |          |      |          | 1.80 |          |     |          | 1.94  |          |     |      |
| 1:4            |           |           | 0.18      |           | 0.17      |           |          |      |          |      |          | 1.76 |          |     |          | 1.7   |          |     |      |
| 1:5            |           |           | 0.09      |           | 0.16      |           |          |      |          |      |          | 0.9  |          |     |          | 1.6   |          |     |      |
| 1:6            |           |           | 0.14      |           | 0.43      |           |          |      |          |      |          | 1.43 |          |     |          | 4.27  |          |     |      |
| 1:7            |           |           | 0.38      |           | 0.70      |           |          |      |          |      |          | 3.84 |          |     |          | 7.03  |          |     |      |
| 1:8            |           |           | 0.26      |           | 0.51      |           |          |      |          |      |          | 2.64 |          |     |          | 5.06  |          |     |      |
| 1:9            |           |           | 0.26      |           | 0.82      |           |          |      |          |      |          | 2.6  |          |     |          | 8.18  |          |     |      |
| CEMI:PFA ratio | Co (mg/l) | Cu (mg/l) | Ni (mg/l) | Se (mg/l) | Ba (mg/l) | Sb (mg/l) | Co limit | Co   | Cu limit | Cu   | Ni limit | Ni   | Se limit | Se  | Ba limit | Ba    | Sb limit | Sb  |      |
| 1:1            | 0.01      | BDL       | 0.02      | BDL       | 1.03      | BDL       | na       | 0.11 | 100      | BDL  | 40       | 0.16 | 7        | BDL | 300      | 10.26 | 5        | BDL |      |
| 1:2            | 0.01      |           | 0.02      |           | 0.42      |           |          | 0.11 |          |      |          | 0.16 |          |     |          | 4.18  |          |     |      |
| 1:3            | 0.01      | 0.01      | 0.02      |           | 0.49      |           |          | 0.12 |          | 0.07 |          | 0.16 |          |     |          | 4.9   |          |     |      |
| 1:4            | 0.01      | BDL       | 0.02      |           | 0.11      |           |          | 0.11 |          | 0.16 |          | 1.06 |          |     |          |       |          |     |      |
| 1:5            | 0.01      |           | 0.02      |           | 0.54      |           |          | 0.1  |          | 0.17 |          | 0.17 |          |     |          | 5.4   |          |     | 0.13 |
| 1:6            | 0.01      | 0.01      | 0.02      |           | 0.26      |           |          | 0.12 |          | 0.04 |          | 0.18 |          |     |          | 2.60  |          |     |      |
| 1:7            | 0.01      | 0.01      | 0.02      |           | BDL       |           |          | 0.11 |          | 0.08 |          | 0.18 |          |     |          | BDL   |          |     | BDL  |
| 1:8            | 0.01      | 0.01      | 0.02      |           | 0.10      |           |          | 0.12 |          | 0.08 |          | 0.15 |          |     |          | 1.01  |          |     |      |
| 1:9            | 0.01      | 0.01      | 0.02      |           | BDL       |           |          | 0.13 |          | 0.08 |          | 0.14 |          |     |          | BDL   |          |     | BDL  |



# Granular Leaching Test Results

| CEM:slag ratio | Pb (mg/l) | Cd (mg/l) | Cr (mg/l) | Zn (mg/l) | Mo (mg/l) | As (mg/l) | Pb limit | Pb   | Cd limit | Cd  | Cr limit | Cr   | Zn limit | Zn  | Mo limit | Mo    | As limit | As  |
|----------------|-----------|-----------|-----------|-----------|-----------|-----------|----------|------|----------|-----|----------|------|----------|-----|----------|-------|----------|-----|
| 1:1            | 0.18      | BDL       | 0.01      | BDL       | 0.03      | BDL       | 50       | BDL  | 5        | BDL | 70       | 0.18 | 200      | BDL | 30       | 0.32  | 25       | BDL |
| 1:2            | 0.27      |           | 0.04      |           | 0.08      |           |          | 2.65 |          |     |          | 0.37 |          |     |          | 0.81  |          |     |
| 1:3            | 0.22      |           | 0.02      |           | 0.11      |           |          | 2.18 |          |     |          | 0.22 |          |     |          | 1.06  |          |     |
| 1:4            | BDL       |           | 0.05      |           | 0.14      |           |          | BDL  |          |     |          | 0.50 |          |     |          | 1.40  |          |     |
| 1:6            | BDL       |           | 0.06      |           | 0.2       |           |          | BDL  |          |     |          | 0.60 |          |     |          | 2.00  |          |     |
| 1:7            | 0.49      |           | 0.07      |           | 0.22      |           |          | 4.9  |          |     |          | 0.70 |          |     |          | 2.20  |          |     |
| 1:8            | BDL       |           | 0.08      |           | 0.26      |           |          | BDL  |          |     |          | 0.57 |          |     |          | 2.60  |          |     |
| CEM:slag ratio | Co (mg/l) | Cu (mg/l) | Ni (mg/l) | Se (mg/l) | Ba (mg/l) | Sb (mg/l) | Co limit | Co   | Cu limit | Cu  | Ni limit | Ni   | Se limit | Se  | Ba limit | Ba    | Sb limit | Sb  |
| 1:1            | 0.01      | BDL       | BDL       | BDL       | 3.29      | BDL       | na       | 0.14 | 100      | BDL | 40       | BDL  | 7        | BDL | 300      | 32.89 | 5        | BDL |
| 1:2            | 0.01      |           | 0.02      |           | 0.01      |           |          | 0.12 |          |     |          | 0.15 |          |     |          | 0.13  |          |     |
| 1:3            | 0.01      |           | BDL       |           | 4.18      |           |          | 0.12 |          |     |          | BDL  |          |     |          | 41.84 |          |     |
| 1:4            | 0.01      |           | 0.02      |           | 4.67      |           |          | 0.10 |          |     |          | 0.20 |          |     |          | 46.70 |          |     |
| 1:6            | 0.01      |           | 0.02      |           | 3.86      |           |          | 0.10 |          |     |          | 0.20 |          |     |          | 38.60 |          |     |
| 1:7            | BDL       |           | BDL       |           | BDL       |           |          | BDL  |          |     |          | BDL  |          |     |          | BDL   |          |     |
| 1:8            | 0.01      |           | 0.02      |           | 0.94      |           |          | 0.10 |          |     |          | 0.15 |          |     |          | 9.43  |          |     |

# **Monolithic Leaching Test**

# The Measured Cumulative Leaching Rates ( $e_n^*$ ) of Contaminants from CEMI-hlime (mg/m<sup>2</sup>) at 28 days

|                  | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        |
|------------------|------------------------------|------------------------|-----------------|------------------------|------------------------------|------------------------|-----------------|------------------------|------------------------------|------------------------|-----------------|------------------------|------------------------------|------------------------|-----------------|------------------------|
|                  | Cr                           |                        | Mo              |                        | Ni                           |                        | Ba              |                        | Cr                           |                        | Mo              |                        | Ni                           |                        | Ba              |                        |
| CEMI:hlime ratio | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) |
| 1:1              | 4                            | 10                     | 2               | 4                      | 2.1                          | 4.2                    | 9               | 80                     | 4                            | 10                     | 2               | 4                      | 2.1                          | 4.2                    | 9               | 80                     |
| 1:2              | 4.4                          | 11.4                   | 1.6             | 4                      | 2.3                          | 4.4                    | 39.2            | 158.5                  | 4.4                          | 11.4                   | 1.6             | 4                      | 2.3                          | 4.4                    | 39.2            | 158.5                  |
| 1:3              | 3                            | 9                      | 0.3             | 0.7                    | 0.2                          | 0.5                    | 31              | 144                    | 3                            | 9                      | 0.3             | 0.7                    | 0.2                          | 0.5                    | 31              | 144                    |
| 1:4              | 3.4                          | 8.3                    | BDL             | BDL                    | 0.3                          | 0.6                    | 53.2            | 147.4                  | 3.4                          | 8.3                    | BDL             | BDL                    | 0.3                          | 0.6                    | 53.2            | 147.4                  |
| 1:5              | 3                            | 8                      | BDL             | BDL                    | 0.2                          | 0.4                    | 63              | 183                    | 3                            | 8                      | BDL             | BDL                    | 0.2                          | 0.4                    | 63              | 183                    |
| 1:6              | 3                            | 8                      | BDL             | BDL                    | 0.5                          | 0.5                    | 39              | 127                    | 3                            | 8                      | BDL             | BDL                    | 0.5                          | 0.5                    | 39              | 127                    |

BDL= below detection limit

$e_n^*$  (mg/m<sup>2</sup>) is obtained by multiplying the metal concentration measured in mg/l with Volume of leaching fluid in litres (l) and divided by area of the test specimen ; A(m<sup>2</sup>).

# The Measured Cumulative Leaching Rates ( $e_n^*$ ) of Contaminants from CEMI-LGMgO (mg/m<sup>2</sup>) at 28 days

|                  | $e_n^*$ (mg/m <sup>2</sup> ) |      |                        |    | $e_n^*$ (mg/m <sup>2</sup> ) |    |                        |    | $e_n^*$ (mg/m <sup>2</sup> ) |      |                        |    | $e_n^*$ (mg/m <sup>2</sup> ) |      |                        |     |
|------------------|------------------------------|------|------------------------|----|------------------------------|----|------------------------|----|------------------------------|------|------------------------|----|------------------------------|------|------------------------|-----|
|                  | Cr                           |      |                        |    | Mo                           |    |                        |    | Ni                           |      |                        |    | Ba                           |      |                        |     |
| CEMI:LGMgO ratio | Compliance (4d)              |      | Characterisation (64d) |    | Compliance (4d)              |    | Characterisation (64d) |    | Compliance (4d)              |      | Characterisation (64d) |    | Compliance (4d)              |      | Characterisation (64d) |     |
| 1:1              | 2.4                          | 6.25 | 5.1                    | 25 | BDL                          | 5  | 0.4                    | 20 | 0.3                          | 3.75 | 0.6                    | 15 | BDL                          | 37.5 | BDL                    | 150 |
| 1:2              | 1.8                          |      | 4.8                    |    | 0.9                          |    | 1.1                    |    | BDL                          |      | BDL                    |    | 4.2                          |      | 7                      |     |
| 1:3              | 4.0                          |      | 9.5                    |    | 2.8                          |    | 4.7                    |    | 2.3                          |      | 4.6                    |    | BDL                          |      | 6.1                    |     |
| 1:4              | 1.2                          |      | 3.4                    |    | BDL                          |    | 0.1                    |    | BDL                          |      | BDL                    |    | 1.7                          |      | 8.8                    |     |
| 1:5              | 3.6                          |      | 7.9                    |    | 2.0                          |    | 6.2                    |    | 2.3                          |      | 4.5                    |    | 0.8                          |      | 7.6                    |     |
| 1:6              | 1.6                          |      | 3.8                    |    | BDL                          |    | 0.3                    |    | 0.2                          |      | 0.4                    |    | BDL                          |      | BDL                    |     |
| 1:7              | 1.7                          |      | 3.5                    |    | 0.4                          |    | 0.4                    |    | 0.3                          |      | 0.6                    |    |                              |      |                        |     |
| 1:8              | 1.8                          |      | 3.5                    |    |                              |    | 0.4                    |    | 0.3                          |      |                        |    |                              |      |                        |     |
| 1:9              | 1.6                          |      | 3.2                    |    | 0.5                          |    | 0.5                    |    | 0.1                          |      | 0.3                    |    |                              |      |                        |     |
|                  | Co                           |      |                        |    | Cu                           |    |                        |    | As                           |      |                        |    |                              |      |                        |     |
|                  | Compliance (4d)              |      | Characterisation (64d) |    | Compliance (4d)              |    | Characterisation (64d) |    | Compliance (4d)              |      | Characterisation (64d) |    |                              |      |                        |     |
| 1:1              | BDL                          | na   | BDL                    | na | BDL                          | 15 | BDL                    | 60 | 1.2                          | 5    | 2.2                    | 20 |                              |      |                        |     |
| 1:2              | 4.5                          |      | 7.9                    |    | 4.9                          |    | 8.5                    |    | 0.3                          |      | 0.3                    |    |                              |      |                        |     |
| 1:3              | 2.9                          |      | 6.6                    |    | 3.0                          |    | 4.8                    |    | BDL                          |      | BDL                    |    |                              |      |                        |     |
| 1:4              | 4.6                          |      | 7.8                    |    | 4.8                          |    | 8.6                    |    |                              |      |                        |    |                              |      |                        |     |
| 1:5              | 3.8                          |      | 6.4                    |    | 3.9                          |    | 5.1                    |    |                              |      |                        |    |                              |      |                        |     |
| 1:6              | BDL                          |      | BDL                    |    | BDL                          |    | BDL                    |    | BDL                          |      | BDL                    |    | 1.3                          | 2.2  |                        |     |
| 1:7              |                              |      |                        |    |                              |    |                        |    |                              |      |                        |    | 0.9                          | 1.8  |                        |     |
| 1:8              |                              |      |                        |    |                              |    |                        |    |                              |      |                        |    | 1.0                          | 1.8  |                        |     |
| 1:9              |                              |      |                        |    |                              |    |                        |    | 1.1                          |      | 1.8                    |    |                              |      |                        |     |

# The Measured Cumulative Leaching Rates ( $e_n^*$ ) of Contaminants from CEMI-PFA (mg/m<sup>2</sup>) at 28 days

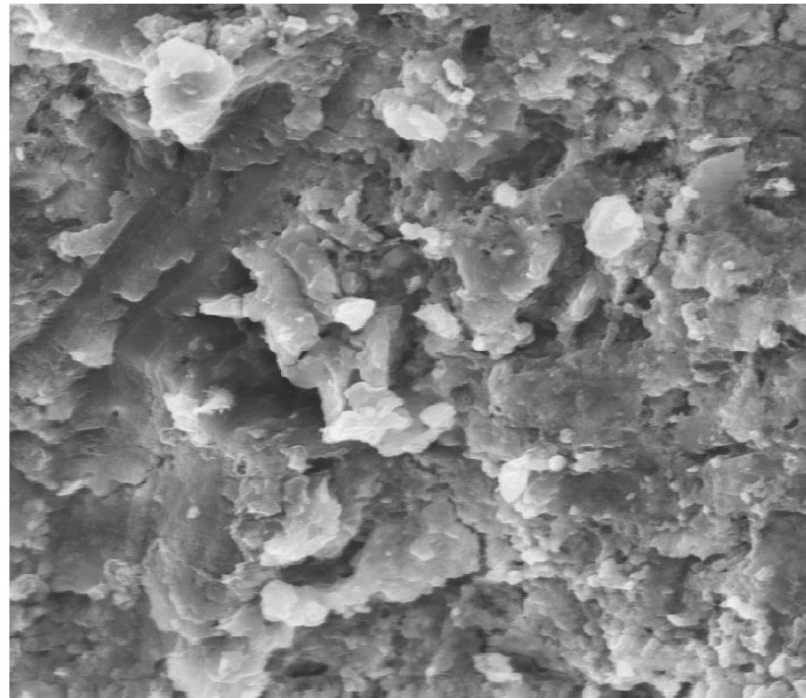
|                | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        |
|----------------|------------------------------|------------------------|-----------------|------------------------|------------------------------|------------------------|-----------------|------------------------|------------------------------|------------------------|-----------------|------------------------|
| CEMI:PFA ratio | Cr                           |                        | Mo              |                        | As                           |                        | Ni              |                        | Ba                           |                        | Sb              |                        |
|                | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) |
| 1:1            | 1.6                          | 6.25                   | 3.6             | 25                     | 10                           | 5                      | 18              | 20                     | 14                           | 5                      | 30              | 20                     |
| 1:2            | 3.7                          |                        | 4.5             |                        | 9.7                          |                        | 18.1            |                        | 16.1                         |                        | 14.0            |                        |
| 1:4            | 7.3                          |                        | 8.6             |                        | 7.8                          |                        | 17.4            |                        | 30.9                         |                        | 30.3            |                        |
| 1:7            | 2.0                          |                        | 4               |                        | na                           |                        | 3               |                        | 2                            |                        | 3               |                        |
| 1:8            | 3                            |                        | 6               |                        | 3                            |                        | 8               |                        | 2                            |                        | 3               |                        |
| 1:9            | 3                            |                        | 9               |                        | 4                            |                        | 17              |                        | 2                            |                        | 3               |                        |
| 1:1            | na                           | 3.75                   | 1               | 15                     | 10                           | 37.5                   | 20              | 150                    | na                           | 0.625                  | 1               | 2.5                    |
| 1:2            | 2.7                          |                        | 2.9             |                        | 4.6                          |                        | 8.5             |                        | 0.5                          |                        | 0.6             |                        |
| 1:4            | 5.5                          |                        | 5.6             |                        | 9.4                          |                        | 17.9            |                        | 0.6                          |                        | 1.4             |                        |
| 1:7            | na                           |                        | 1               |                        | na                           |                        | na              |                        | na                           |                        | na              |                        |
| 1:8            |                              |                        | 1               |                        |                              |                        |                 |                        |                              |                        |                 |                        |
| 1:9            |                              |                        | 1               |                        |                              |                        |                 |                        |                              |                        |                 |                        |



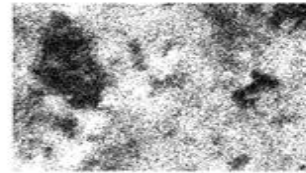
# The Measured Cumulative Leaching Rates ( $e_n^*$ ) of Contaminants from CEMI-steel slag (mg/m<sup>2</sup>) at 28 days

|                 | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        | $e_n^*$ (mg/m <sup>2</sup> ) |                        |                 |                        |
|-----------------|------------------------------|------------------------|-----------------|------------------------|------------------------------|------------------------|-----------------|------------------------|------------------------------|------------------------|-----------------|------------------------|
| CEMI:slag ratio | Cr                           |                        | Mo              |                        | As                           |                        | Ni              |                        | Ba                           |                        | Sb              |                        |
|                 | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) |
| 1:1             | 2.8                          | 6.25                   | 5.6             | 25                     | 7.6                          | 5                      | 14.3            | 20                     | 14.7                         | 5                      | 27.9            | 20                     |
| 1:2             | 3.1                          |                        | 6.3             |                        | 8.3                          |                        | 16.9            |                        | 16.2                         |                        | 32.3            |                        |
| 1:3             | 2.8                          |                        | 5.6             |                        | 8.3                          |                        | 15.9            |                        | 14.4                         |                        | 26.6            |                        |
| 1:4             | 3.5                          |                        | 7.2             |                        | 10.2                         |                        | 20.5            |                        | 13.6                         |                        | 27.5            |                        |
| 1:5             | 2.8                          |                        | 5.9             |                        | 8.1                          |                        | 18.1            |                        | 12.7                         |                        | 24.2            |                        |
| 1:6             | 2.6                          |                        | 5.5             |                        | 7.1                          |                        | 16.9            |                        | 13.8                         |                        | 28.5            |                        |
| 1:7             | 2.8                          |                        | 5.3             |                        | 8.5                          |                        | 16.6            |                        | 11.6                         |                        | 21.6            |                        |
| 1:8             | 3.1                          |                        | 5.7             |                        | 9.4                          |                        | 17.8            |                        | 10.8                         |                        | 19.8            |                        |
|                 | Ni                           |                        | Ba              |                        | Sb                           |                        | Ni              |                        | Ba                           |                        | Sb              |                        |
|                 | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) | Compliance (4d)              | Characterisation (64d) | Compliance (4d) | Characterisation (64d) |
| 1:1             | 1.4                          | 3.7                    | 2.8             | 15                     | 4.3                          | 37.5                   | 12.6            | 150                    | 0.1                          | 0.62                   | 1.1             | 2.5                    |
| 1:2             | 1.7                          |                        | 3.6             |                        | 7.4                          |                        | 21.6            |                        | 0.6                          |                        | 2.4             |                        |
| 1:3             | 1.2                          |                        | 2.7             |                        | 12.4                         |                        | 39.2            |                        | 1.8                          |                        | 2.0             |                        |
| 1:4             | 1.8                          |                        | 3.6             |                        | 16.4                         |                        | 57.9            |                        | 0.7                          |                        | 2.1             |                        |
| 1:5             | 1.3                          |                        | 2.7             |                        | 16.2                         |                        | 54.0            |                        | 0.8                          |                        | 2.6             |                        |
| 1:6             | 1.2                          |                        | 2.6             |                        | 13.1                         |                        | 53.1            |                        | 0.9                          |                        | 2.0             |                        |
| 1:7             | 1.3                          |                        | 2.4             |                        | 0                            |                        | 0               |                        | 0                            |                        | 0               |                        |
| 1:8             | 1.1                          |                        | 2.1             |                        | 0                            |                        | 0               |                        | 0                            |                        | 0               |                        |

# SEM image of CEMI-LGMgO 1:2 at 28 days' curing age



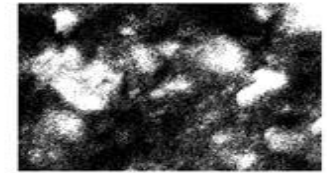
40 μm



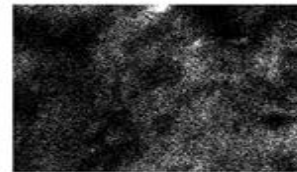
Ca Ka1



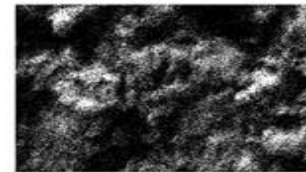
C Ka1\_2



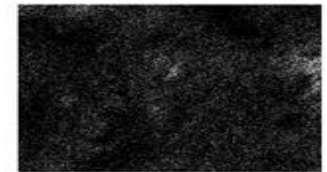
Mg Ka1\_2



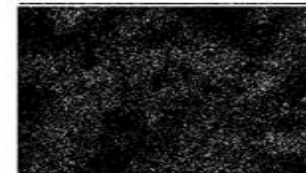
Si Ka1



O Ka1

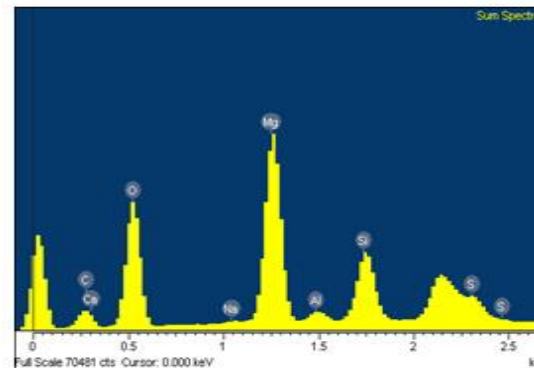


S Ka1



Na Ka1\_2

EDX elemental Maps of CEMI-LGMgO 1:2:0 with distribution of C, O, Mg, Si, Ca, Na, S

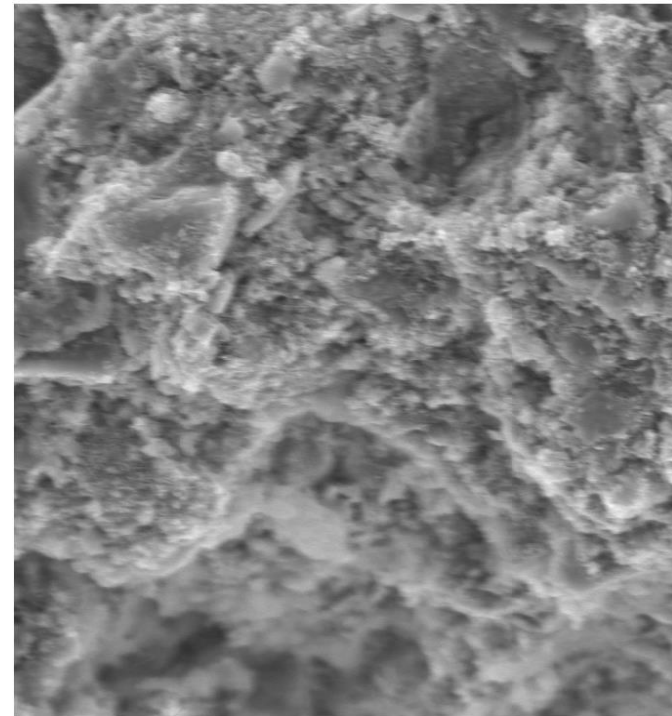


Sum spectrum of LGMgO 1:2:0 at 28 days

Quantification of  
CEMI-LGMgO 1:2:0

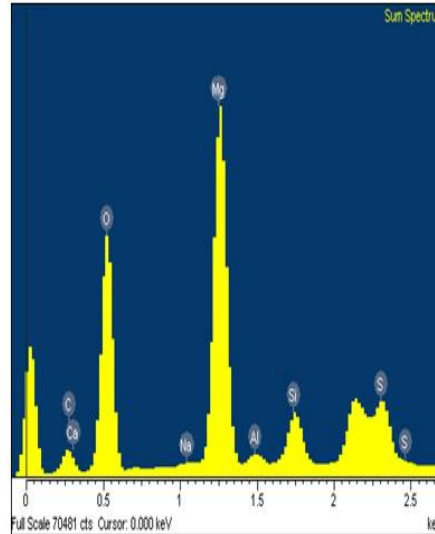
| Element | Weight % | Atom% c% |
|---------|----------|----------|
| C K     | 7.41     | 12.26    |
| O K     | 48.50    | 60.28    |
| Na K    | 0.27     | 0.23     |
| Mg K    | 13.55    | 11.08    |
| Al K    | 0.68     | 0.50     |
| Si K    | 4.27     | 3.03     |
| S K     | 0.42     | 0.26     |
| Ca K    | 24.90    | 12.36    |
| Totals  | 100.00   |          |

# SEM image of CEMI-LGMgO 1:4 at 28 days' curing age



60µm

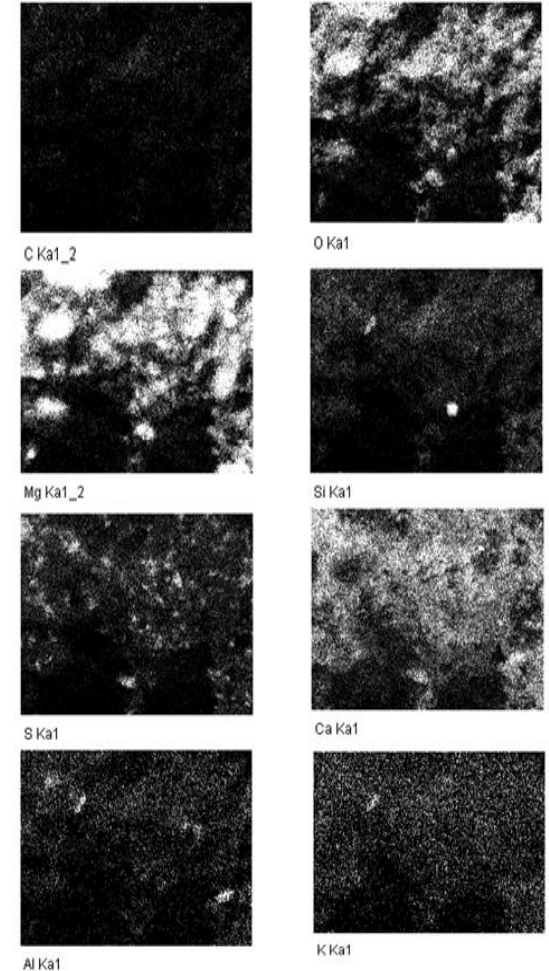
Electron Image



Sum spectrum of CEMI-LGMgO 1:4:0

Quantification of CEMI-LGMgO 1:4:0

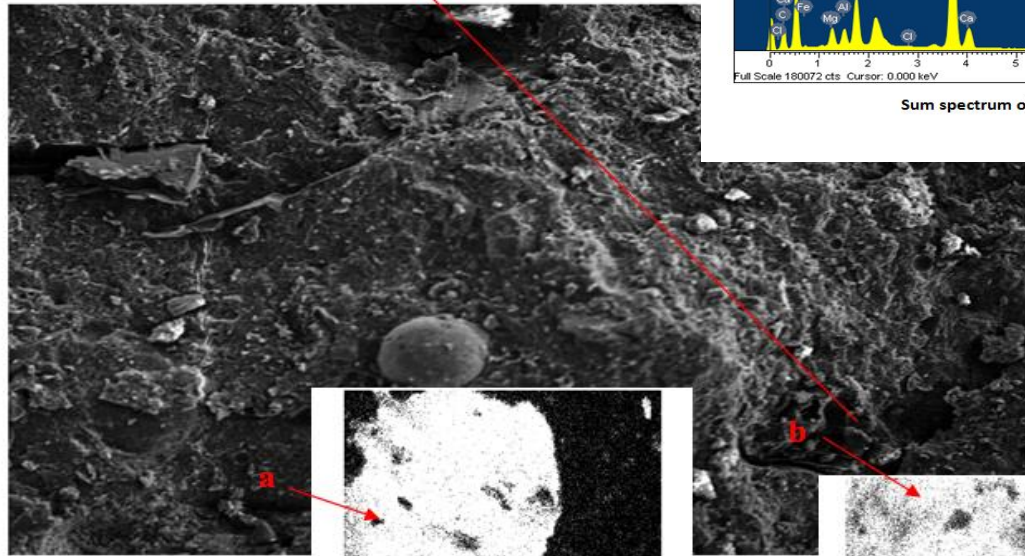
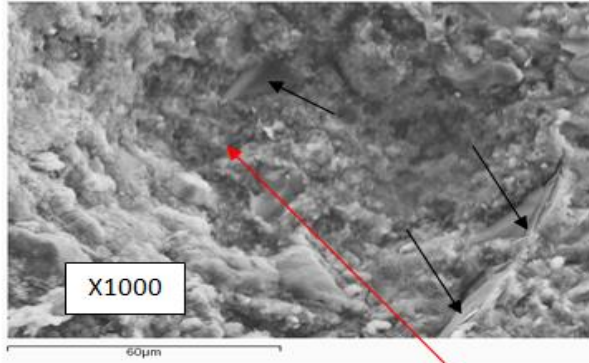
| Element | Weight % | Atomic % |
|---------|----------|----------|
| C K     | 7.99     | 12.58    |
| O K     | 52.43    | 62.01    |
| Na K    | 0.35     | 0.29     |
| Mg K    | 18.73    | 14.58    |
| Al K    | 0.58     | 0.40     |
| Si K    | 2.49     | 1.68     |
| S K     | 1.94     | 1.14     |
| Ca K    | 15.50    | 7.32     |
| Totals  | 100.00   |          |



EDX elemental maps of CEMI-LGMgO 1:4:0 with distribution of C, O, Mg, Si, S, Al, K and Ca



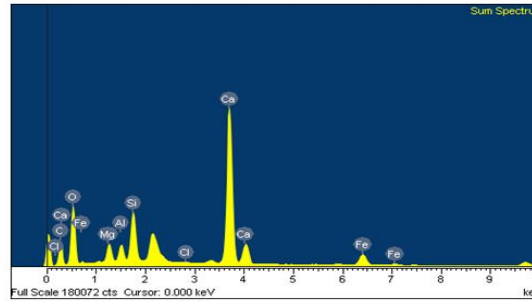
# SEM image of CEMI-slag 1:2 at 28 days' curing age



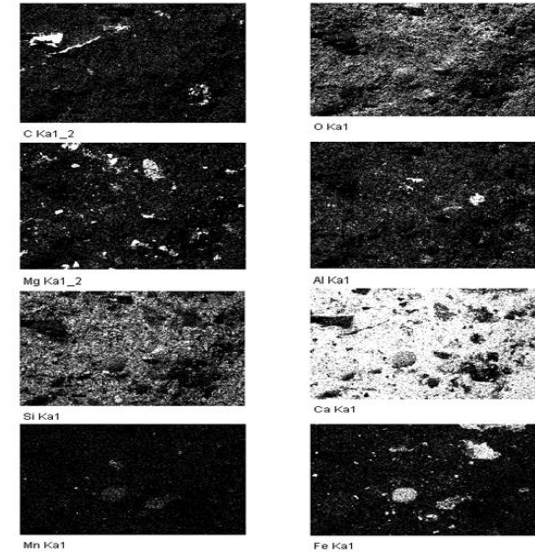
Fe Ka1

Quantification of CEMI-slag 1:2:0

| Element | Weight% | Atomic% |
|---------|---------|---------|
| C K     | 15.61   | 25.29   |
| O K     | 44.21   | 53.76   |
| Mg K    | 2.53    | 2.02    |
| Al K    | 1.77    | 1.28    |
| Si K    | 5.03    | 3.48    |
| Cl K    | 0.07    | 0.04    |
| Ca K    | 24.83   | 12.05   |
| Fe L    | 5.95    | 2.07    |
| Total   | 100.00  | 100.00  |



Sum spectrum of CEMI-slag 1:2:0

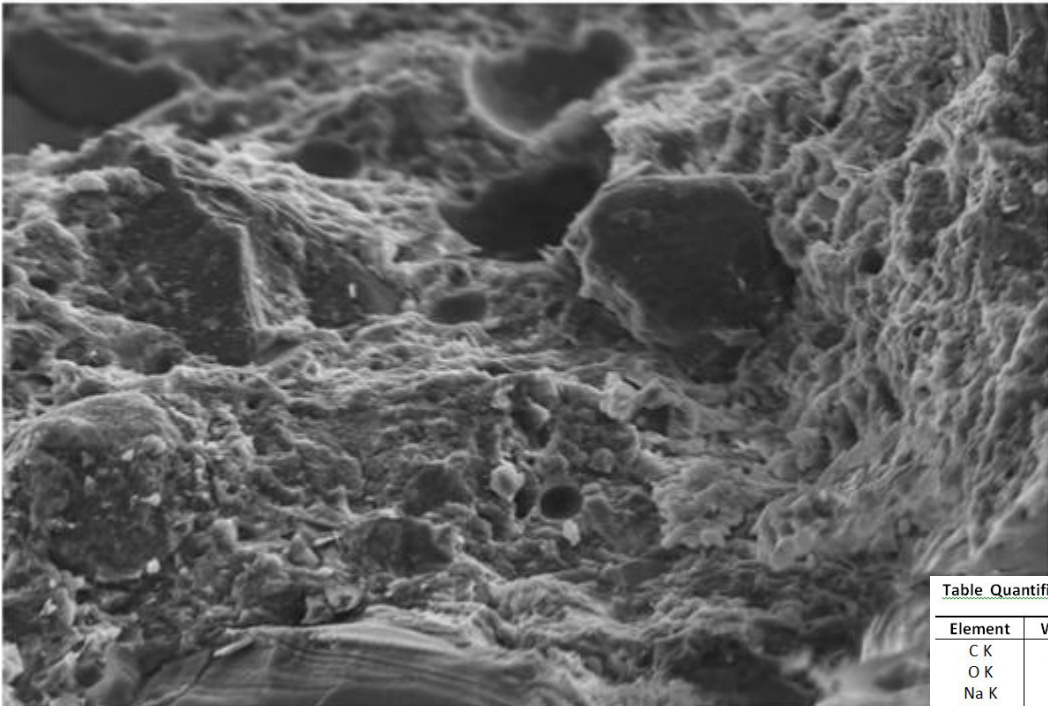


EDX elemental maps of CEMI-slag 1:2:0 with distribution of C, O, Mg, Al, Si, Ca, Mn and Fe.

Ca Ka1

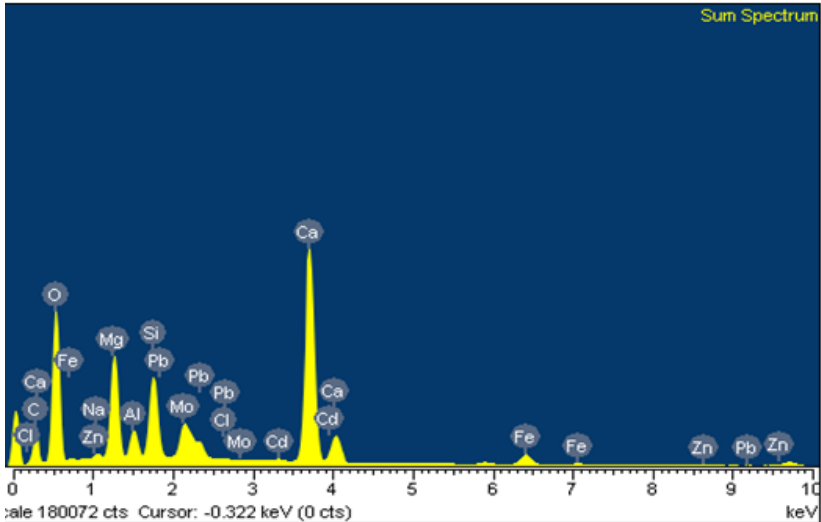
SEM image of CEMI-slag 1:2 at 28 days – large area scan (X90)

# SEM image of CEMI-slag 1:4 at 28 days' curing age



100µm

SEM image of CEMI-slag 1:4



Sum spectrum of CEMI-slag 1:4:0

Table Quantification of CEMI-slag 1:4:0

| Element | Weight% | Atomic% |
|---------|---------|---------|
| C K     | 14.59   | 22.73   |
| O K     | 49.00   | 57.29   |
| Na K    | 0.38    | 0.31    |
| Mg K    | 7.31    | 5.62    |
| Al K    | 1.59    | 1.10    |
| Si K    | 4.58    | 3.05    |
| Cl K    | 0.10    | 0.05    |
| Ca K    | 17.86   | 8.34    |
| Fe L    | 4.09    | 1.37    |
| Zn K    | 0.49    | 0.14    |
| Total   | 100.00  | 100.00  |

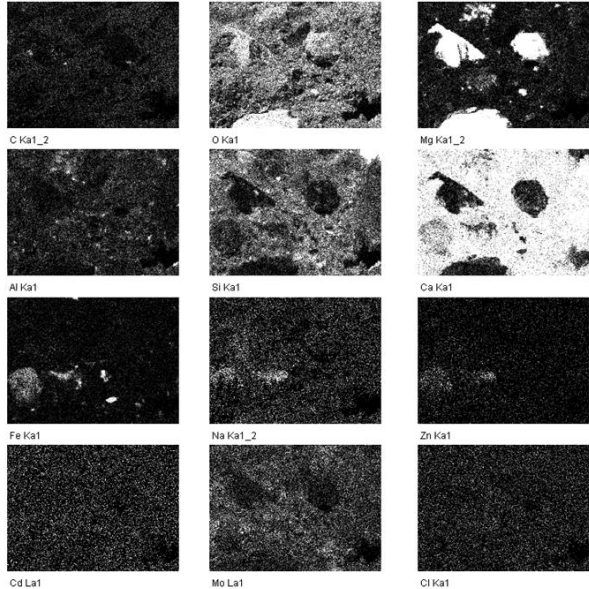


Figure EDX Elemental Maps of CEMI-slag 1:4:0 with distribution of C, O, Mg, Al, Si, Ca, Fe, Cd, Na, Zn, Mo and Cl



# XRD Results

## Quantitative Analysis -Rietveld

### CEMI

|                              |      |
|------------------------------|------|
| Phase 1 : <u>Periclase</u>   | 1%   |
| Phase 2 : <u>Portlandite</u> | 1 %  |
| Phase 3 : <u>Calcite</u>     | 1 %  |
| Phase 4 : <u>Gypsum</u>      | 2 %  |
| Phase 5 : <u>Alite</u>       | 65 % |
| Phase 6 : <u>Belite</u>      | 15 % |
| Phase 7 : <u>Ferrite</u>     | 6 %  |
| Phase 8 : <u>Aluminate</u>   | 5 %  |
| Phase 9 : <u>Quartz</u>      | 1 %  |
| Phase 10 : <u>Lime</u>       | 1 %  |
| Phase 11 : <u>Anhydrite</u>  | 1 %  |

### CEMI-LGMgO 1:2

|                                                 |         |
|-------------------------------------------------|---------|
| Phase 1 : <u>Periclase</u>                      | 23.40 % |
| Phase 2 : <u>Portlandite</u>                    | 4.94 %  |
| Phase 3 : <u>Calcite</u>                        | 12.68 % |
| Phase 4 : <u>Gypsum</u>                         | 2.16 %  |
| Phase 5 : <u>Aragonite</u>                      | 6.99 %  |
| Phase 6 : <u>Dolomite</u>                       | 2.07 %  |
| Phase 7 : <u>Magnesite</u>                      | 0.66 %  |
| Phase 8 : <u>Ettringite</u>                     | 4.82 %  |
| Phase 9 : <u>Quartz</u>                         | 1.61 %  |
| Phase 10 : <u>"C<sub>2</sub>S beta (MUMME)"</u> | 5.93 %  |
| Phase 11 : <u>Brucite</u>                       | 34.75 % |

### CEMI-LGMgO 1:4

|                                       |         |
|---------------------------------------|---------|
| Phase 1 : <u>Periclase</u>            | 25.58 % |
| Phase 2 : <u>Portlandite</u>          | 0.81 %  |
| Phase 3 : <u>Calcite</u>              | 8.34 %  |
| Phase 4 : <u>Gypsum</u>               | 6.36 %  |
| Phase 5 : <u>Aragonite</u>            | 8.16 %  |
| Phase 6 : <u>Dolomite</u>             | 2.49 %  |
| Phase 7 : <u>Magnesite</u>            | 0.85 %  |
| Phase 8 : <u>Ettringite</u>           | 1.55 %  |
| Phase 9 : <u>Quartz</u>               | 0.89 %  |
| Phase 10 : <u>C<sub>2</sub>S beta</u> | 2.73 %  |
| Phase 11 : <u>Brucite</u>             | 41.40 % |

### CEMI-slag 1:2

|                                               |         |
|-----------------------------------------------|---------|
| Phase 1: <u>Periclase</u>                     | 20.25 % |
| Phase 2: <u>Calcite</u>                       | 22.63 % |
| Phase 3: <u>Portlandite</u>                   | 6.02 %  |
| Phase 4: <u>Quartz</u>                        | 4.41 %  |
| Phase 5: <u>Vaterite</u>                      | 17.33 % |
| Phase 6: <u>Aragonite</u>                     | 15.45 % |
| Phase 7: <u>"C<sub>2</sub>S beta (MUMME)"</u> | 11.27 % |
| Phase 8: <u>"Annite mica"</u>                 | 2.64 %  |

### CEMI-slag 1:4

|                                               |         |
|-----------------------------------------------|---------|
| Phase 1: <u>Periclase</u>                     | 11.59 % |
| Phase 2: <u>Calcite</u>                       | 22.28 % |
| Phase 3: <u>Portlandite</u>                   | 8.29 %  |
| Phase 4: <u>Quartz</u>                        | 2.86 %  |
| Phase 5: <u>Vaterite</u>                      | 5.03 %  |
| Phase 6: <u>Aragonite</u>                     | 7.79 %  |
| Phase 7: <u>"C<sub>2</sub>S beta (MUMME)"</u> | 16.23 % |
| Phase 8: <u>Ettringite</u>                    | 6.75 %  |
| Phase 9: <u>Gypsum</u>                        | 18.98 % |

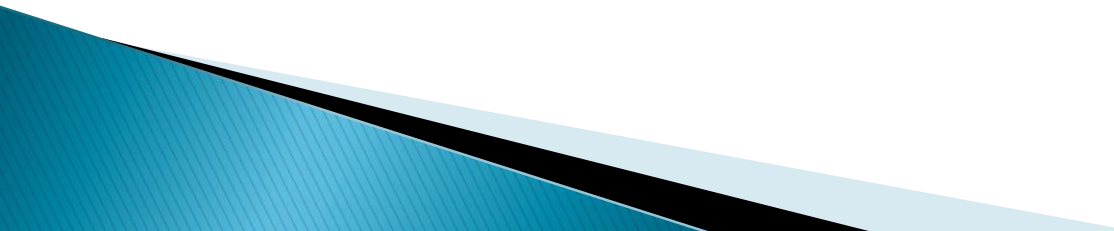
# CONCLUSIONS

- ▶ LGMgO, PFA and slag blended mixtures performed well in terms of physical integrity - UCS development at ALL ratios studied (1:1 to 1:9).
- ▶ Leaching test results clearly showed that the use of LGMgO, steel slag, PFA and hlime as alternative binders for EAFD S/S exhibited much better product performance in terms of granular leaching test regime when compared to the monolithic one.





# CONCLUSIONS

- ▶ SEM analysis was able to detect the formation of cement hydration products (portlandite and ettringite) formation of C-H and/or C-S-H cement hydration products.
  - ▶ Effective replacement of cement by LGMgO and steel slag (both waste by-products) at a ratio of 1:4 significantly improves both the economics and sustainability characteristics of this treatment technique.
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**Thanks for Listening! 😊**  
**Any Questions, please?!**





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