**Appendix File**

This file provides the detailed life cycle inventories for determining the production environmental impacts of PRAC and DRAC. If interested, readers can refer to Gursel’s PhD thesis (2014) for more introductions on the main principles of life cycle assessment simulations.

**Table A** Cement plant technology options

|  |  |  |
| --- | --- | --- |
| Cement production phases | Product of each phase | Technology selection |
| Raw materials prehomogenization | Raw meal | Wet process\_raw storing |
| Raw materials grinding | Ground meal | Dry raw grinding\_tube mill |
| Raw meal blending&homogenization | Blended meal | Raw meal homogenization, blending and storage |
| Pyroprocessing | Clinker | China-average kiln |
| Clinker cooling | Cooled clinker | Rotar (tube) cooler |
| Finish milling, grinding and blending | OPC/blended cement | Roller press |
| Clinker cooling PM control | — | Fabric filter (FF) |

**Table B** Fuel use options for cement pyroprocessing

|  |  |
| --- | --- |
| Fuel type | Proportion |
| Bituminous coal | 64.1% |
| Petroleum coke (pet coke) | 21.2% |
| Natural gas | 3.7% |
| Residual (heavy) fuel oil | 0.2% |
| Distillate (diesel or light) fuel oil | 0.8% |
| Waste oil | 0.3% |
| Waste solvent | 4.0% |
| Waste tires (whole) | 1.8% |
| Waste tires (shredded) | 1.8% |
| Waste (other) (non-hazardous) | 2.3% |

**Table C** Life cycle inventory for freight transportation (Gursel, 2014; GB30510, 2018)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Transport mean | Road\_class 8b | Road\_class 5 | Road\_class 2b | Rail\_interstate | Water\_general cargo |
| Energy cost (MJ/ton/km) | 1.03E+0 | 1.77E+0 | 2.97E+0 | 3.10E-1 | 2.49E-1 |
| Air emissions (kg/ton/km) | | | | | |
| CO2-eq | 1.28E-1 | 1.58E-1 | 1.98E-1 | 2.74E-2 | 1.72E-2 |
| CO2 | 1.28E-1 | 1.58E-1 | 1.98E-1 | 2.74E-2 | 1.65E-2 |
| CO | 4.11E-4 | 8.22E-4 | 1.26E-3 | 2.88E-4 | 0 |
| NOx | 1.76E-3 | 1.12E-3 | 1.21E-3 | 5.07E-4 | 3.80E-4 |
| PM10 | 2.40E-4 | 3.22E-4 | 4.04E-4 | 3.42E-5 | 0 |
| SO2 | 1.03E-4 | 2.05E-4 | 3.08E-4 | 8.22E-5 | 7.30E-5 |

**Table D** Life cycle inventory for cement raw materials quarrying (Gursel, 2014)

|  |  |  |
| --- | --- | --- |
| Energy or raw material use | Unit | Single quantity (per tonne of raw material) |
| Bituminous (hard) coal | kg | 0.036 |
| Natural gas | m3 | 0.140 |
| Distillate (diesel or light) fuel oil | l | 0.584 |
| Gasoline | l | 0.051 |
| Electricity | kWh | 4.230 |
| Water | m3 | 4.351 |

**Table E** Life cycle inventory for cement raw meal preparation (Gursel, 2014)

|  |  |  |  |
| --- | --- | --- | --- |
| Process and technology option | Electricity  (kWh/tonne clinker) | Water  (m3/tonne material) | PM10  (m3/tonne material) |
| **Raw materials prehomogenization** | | | |
| Wet process\_raw storing | 0.375 | 0 | 0.750 |
| **Raw materials grinding** | | | |
| Dry raw grinding\_tube mill | 18.5 | 0 | 7E-4 |
| **Raw meal blending & homogenization** | | | |
| Raw meal homogenization, blending and storage | 1.08 | 0 | 0 |

**Table F** Life cycle inventory for cement pyroprocessing (Gursel, 2014)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Thermal energy consumption** (MJ/kg clinker) | | | | | | |
| Avg. | Max. | | | | Min. | |
| 3.5 | 3.8 | | | | 3.1 | |
| **Electricity use** (kWh/tonne clinker) | | | | | | |
| Avg. | Max. | | | | Min. | |
| 25.0 | 25.0 | | | | 25.0 | |
| **Water consumption** (kg/tonne cement) | | | **PM10 emission** (kg/tonne cement) | | | |
| Avg. | | | Avg. | | | |
| 88.0 | | | 0.232 | | | |
|  | | Avg. | | Max. | | Min. |
| **CKD generation** (kg/tonne cement) | | 38.6 | | 38.6 | | 38.6 |
| **CO2 emission** (kg/tonne cement) | | 522.0 | | 522.0 | | 522.0 |

**Table G** Life cycle inventory for cement cooling (Gursel, 2014)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **PM control technology and amount** (-/tonne cement) | | | | | | |
| Technique option | Electricity use (kWh) | | | | PM amount (kg) | |
| Avg. | Max. | | Min. |
| Fabric filter (FF) | 1.902 | 2.092 | | 1.712 | 6E-5 | |
| **Electricity use for clinker cooling** (kWh/tonne cement) | | | | | | |
| Technology option | Avg. | | Max. | | | Min. |
| Rotar (tube) cooler | 3.563 | | 3.800 | | | 3.325 |
| **Water use for clinker cooling** (m3/tonne clinker) | | | | | | |
| Technology option | Avg. | | Max. | | | Min. |
| Rotar (tube) cooler | 0.030 | | 0.060 | | | 0 |

**Table H** Life cycle inventory for clinker finish milling and grinding (Gursel, 2014)

|  |  |  |  |
| --- | --- | --- | --- |
| Electricity use (kWh/tonne cement) | | | |
| Technology option | Avg. | Max. | Min. |
| Roller press | 27.5 | 33.0 | 22.0 |

**Table I** Life cycle inventory for cement plant conveying (Gursel, 2014)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Conveyor technology | Screw pump | Airlift | Dense phase pump | Bucket elevator |
| Electricity use (kWh/kg/m) | 1.2E-6 | 1.1E-5 | 5.9E-6 | 4.1E-6 |

**Table J** Life cycle inventory for gypsum production (Gursel, 2014)

|  |  |
| --- | --- |
| Energy use & waste emission | Single quantity (per kg of gypsum) |
| Diesel (distillate) fuel oil (l) | 4.67E-4 |
| Electricity (kWh) | 9.16E-4 |
| PM10 (kg) | 1.12E-4 |

**Table K** Life cycle inventory for fly-ash secondary processing (Chen et al., 2010)

|  |  |
| --- | --- |
| Energy use & waste emission | Single quantity (per tonne of fly ash) |
| Natural gas (m3) | 7.59 |
| Distillate (diesel or light) fuel oil (l) | 1.03 |
| Electricity (kWh) | 6.82 |
| PM (kg) | 3.23 |
| Solid waste (kg) | 8.48 |

**Table L** Life cycle inventory for GBFS secondary processing (Chen et al., 2010)

|  |  |
| --- | --- |
| Energy use & waste emission | Single quantity (per tonne of GBFS) |
| Natural gas (m3) | 8.96 |
| Distillate (diesel or light) fuel oil (l) | 1.26 |
| Electricity (kWh) | 94.70 |
| Water (m3) | 0.92 |
| PM (kg) | 0.22 |
| Solid waste (kg) | 0.31 |

**Table M** Life cycle inventory for sand production (Gursel, 2014)

|  |  |
| --- | --- |
| Energy cost and waste emissions | (per kg of aggregate) |
| Electricity (kWh) | 0 |
| Natural gas (m3) | 0 |
| Residual (heavy) fuel oil (l) | 2.86E-4 |
| Distillate (diesel or light) fuel oil (l) | 0 |
| Gasonline (l) | 0 |
| Water (m3) | 0 |

**Table N** Life cycle inventory for coarse natural aggregate production (Ghanbari et al., 2018)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Machine and model | Numbers required in 200 tons/h plant | Power (kW) | Energy source | Efficiency |
| Bulldozer. Komatsu D155A-2 | 2 | 238.6 | Diesel | 0.71 |
| Hydraulic excavator. Komatsu PC 600-7 | 3 | 287 | Diesel | 0.75 |
| Wheel loader. Komatsu WA420-3 | 2 | 162 | Diesel | 0.75 |
| Rigid dump truck. Komatsu HD325-6 | 1 | 364 | Diesel | 0.8 |
| Lorry truck. Benz Wh 2624 | 4 | 179 | Diesel | 0.82 |
| Backhoe loader. HEPCO B90B | 1 | 72 | Diesel | 0.65 |
| Primary-jaw crusher | 1 | 165 | Electricity | 1 |
| Secondary-hydro cone crusher | 2 | 125 | Electricity | 1 |
| Tertiary-impact crusher | 1 | 195 | Electricity | 1 |
| Vibrating feeder | 2 | 16 | Electricity | 1 |
| Vibrating screening | 3 | 19 | Electricity | 1 |
| Bucket-typed sand washing machine | 1 | 18 | Electricity | 1 |
| pan-typed aggregate washing machine | 3 | 20 | Electricity | 1 |
| Conveyor belt 1.2×35 | 4 | 18 | Electricity | 1 |
| Conveyor belt 1.2×21 | 4 | 12.5 | Electricity | 1 |
| Conveyor belt 1× 15 | 3 | 8 | Electricity | 1 |
| Conveyor belt 1×8 | 2 | 6.5 | Electricity | 1 |
| Conveyor belt 1.2×4 | 1 | 5 | Electricity | 1 |
| Conveyor belt 1×3.5 | 2 | 4 | Electricity | 1 |

**Table O** Life cycle inventory for coarse recycled aggregate production (Ghanbari et al., 2018)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Machine and model | Numbers required in 200 tons/h plant | Power (kW) | Energy source | Efficiency |
| Hydraulic excavator. Komatsu PC 200-7 | 1 | 107 | Diesel | 0.7 |
| Wheel loader. VOLVO L120F | 1 | 179 | Diesel | 0.73 |
| Vibrating feeder | 1 | 15 | Electricity | 1 |
| Primary-jaw crusher | 1 | 90 | Electricity | 1 |
| Secondary- impact crusher | 1 | 250 | Electricity | 1 |
| Vibrating screening | 1 | 30 | Electricity | 1 |
| Magnetic separator | 1 | 3 | Electricity | 1 |
| Soft products separator | 2 | 5.5 | Electricity | 1 |
| Dust collector | 1 | 85 | Electricity | 1 |
| Conveyor belt 1×11 | 1 | 7.5 | Electricity | 1 |
| Conveyor belt 1.2×10 | 1 | 5.5 | Electricity | 1 |
| Conveyor belt 1×19 | 1 | 11 | Electricity | 1 |
| Conveyor belt 1×25 | 1 | 15 | Electricity | 1 |
| Conveyor belt 1×10 | 1 | 4 | Electricity | 1 |
| Conveyor belt 0.8×16 | 1 | 7.5 | Electricity | 1 |
| Conveyor belt 0.65×20 | 2 | 7.5 | Electricity | 1 |
| Conveyor belt 0.65×12 | 1 | 5.5 | Electricity | 1 |
| Conveyor belt 0.65×15 | 1 | 5.5 | Electricity | 1 |
| Conveyor belt 0.65×18 | 1 | 5.5 | Electricity | 1 |

**Table P** Life cycle inventory for admixture production (Gursel, 2014)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Admixture type | Plasticiser | Superplasticiser | Retarder | Accelerator | Air entraining | Waterproofing |
| Single quantity (per kg of admixture) | | | | | | |
| Energy use (MJ) | 4.60 | 1.83E+1 | 1.77E+1 | 2.28E+1 | 2.1E+0 | 5.60E+0 |
| Solid waste (kg) |  | | | | | |
| Non-hazardous solid waste (kg) | 3.40E-3 | 2.10E-2 | 9.10E-2 | 3.20E-3 | 2.90E-4 | 2.40E-5 |
| Hazardous solid waste (kg) | 1.70E-4 | 4.50E-4 | 7.40E-4 | 1.20E-4 | 5.90E-5 | 7.40E-5 |
| Air emissions | | | | | | |
| CO2-eq (kg) | 2.29E-1 | 7.67E-1 | 1.42 | 1.26 | 1.03E-1 | 3.74E-1 |
| As (kg) | 4.70E-8 | 5.80E-8 | 1.60E-8 | 1.80E-7 | 8.60E-9 | 4.40E-8 |
| CO2 (kg) | 2.20E-1 | 7.20E-1 | 7.60E-2 | 1.20 | 8.60E-2 | 2.50E-1 |
| CO (kg) | 1.10E-4 | 5.50E-4 | 8.10E-4 | 1.00E-3 | 1.10E-4 | 5.70E-4 |
| Cr (kg) | 6.80E-10 | 1.60E-8 | 5.60E-9 | 6.70E-8 | 3.30E-9 | 1.70E-8 |
| Hg (kg) | 2.80E-9 | 9.40E-8 | 2.90E-8 | 3.40E-8 | 1.90E-8 | 9.20E-9 |
| CH4 (kg) | 3.80E-4 | 1.20E-3 | 5.80E-2 | 2.50E-3 | 6.20E-4 | 2.80E-3 |
| Ni (kg) | 9.30E-7 | 4.60E-7 | 1.50E-7 | 1.70E-6 | 4.60E-8 | 4.20E-7 |
| NOx (kg) | 5.20E-4 | 1.80E-3 | 1.70E-3 | 2.30E-3 | 3.50E-4 | 1.60E-3 |
| N2O (kg) | 0 | 6.70E-5 | 3.50E-5 | 0 | 8.60E-6 | 2.00E-4 |
| SO2 (kg) | 8.50E-4 | 3.60E-3 | 1.40E-3 | 2.80E-3 | 3.20E-4 | 8.80E-4 |
| VOC (unspecified) (kg) | 1.70E-4 | 2.90E-4 | 0 | 0 | 0 | 0 |

**Table Q** Life cycle inventory for water extracting and treatment (GaBi, 2020; Stokes and Horvath, 2009)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| User choice | Single quantity (per m3 of water) | | | |
| Electricity (kWh) | CO2 (kg) | CH4 (kg) | N2O (kg) |
| Self-supplied industrial surface water | 7.90E-2 | 0 | 0 | 0 |
| Public surface water | 4.82E-1 | 2.90E-2 | 0 | 0 |
| Self-supplied industrial groundwater | 1.85E-1 | 0 | 0 | 0 |
| Public groundwater | 6.61E-1 | 7.37E-3 | 0 | 0 |
| Seawater | 7.90E-2 | 0 | 0 | 0 |

**Table R** Life cycle inventory for concrete mixing and batching (Gursel, 2014)

|  |  |
| --- | --- |
| Energy and water | Single quantity (per m3 of concrete) |
| Natural gas (m3) | 3.28E-9 |
| Distillate (diesel or light) fuel oil (l) | 4.38E-7 |
| Electricity (kWh) | 4.11 |
| Water, excluding batch water (m3) | 6.50E-1 |
| Waste emissions | |
| Solid waste (kg) | 2.40E+1 |
| PM | See Table S |

**Table S** PM emission inventory for concrete mixing and batching (Gursel, 2014)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Material | Single quantity (kg per tonne of material) | | | |
| Emission control with FF | | Uncontrolled | |
| PM10 | PMtotal | PM10 | PMtotal |
| Cement | 1.70E-4 | 5.00E-4 | 2.40E-1 | 3.60E-1 |
| Water | 0 | 0 | 0 | 0 |
| Fine aggregates | 0 | 0 | 5.10E-4 | 1.10E-3 |
| Coarse aggregates | 0 | 0 | 1.70E-3 | 3.50E-3 |
| FA | 2.40E-3 | 4.50E-3 | 6.50E-1 | 1.57 |
| GBFS | 2.40E-3 | 4.50E-3 | 6.50E-1 | 1.57 |
| Superplasticiser | 0 | 0 | 0 | 0 |
| Mixer loading (central mix) | 2.80E-3 | 9.20E-3 | 7.80E-2 | 2.86E-1 |
| Truck loading (truck mix) | 1.31E-2 | 4.90E-3 | 1.55E-1 | 5.59E-1 |
| Fine aggregates loading weight hopper | 0 | 0 | 1.30E-3 | 2.60E-3 |
| Coarse aggregates-loading weight hopper | 0 | 0 | 1.30E-3 | 2.60E-3 |

Life cycle inventories for **fuel pre-combustion and combustion** can see Gursel (2014) for more details.

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