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Reducing water footprint of building sector: concrete with seawater and marine aggregates

Arosio V¹, Arrigoni A², Dotelli G¹

¹ Dipartimento di Chimica, Materiali e Ingegneria Chimica, Politecnico di Milano, Piazza Leonardo da Vinci 32, Milano, 20133, Italy

² Department of Civil and Mineral Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario M5S 1A4, Canada

valeria.arosio@mail.polimi.it

Abstract. Freshwater resources are currently under great pressure all over the world due to many factors, such as climate change and growing urbanization. Industrial products like concrete pauperize a significant share of available freshwater during their life cycle. Therefore, cutting down the amount of freshwater consumed by these products might be a solution to reduce the stress in regions affected by water scarcity. In this study, the potential freshwater savings linked to the adoption of innovative concrete mixtures were investigated via the Life Cycle Assessment (LCA) method. In particular, the use of marine aggregates instead of land-based ones and seawater rather than freshwater in the mixing process of concrete were examined. To improve the validity of the analysis, the applicability to the Italian context using geo-referenced data for the distance to the coastline and the availability of freshwater was explored. Results confirmed the positive effect that the use of seawater and marine aggregates might have in reducing the water footprint of the Italian construction sector, leaving freshwater available for human consumption. Mixing concrete with seawater would lead to a reduction of its water footprint up to 12%. Moreover, if land-won aggregates were replaced with marine ones, an 84% reduction of the water footprint could be achieved. In both cases, possible burden shifting (e.g. increase of greenhouse gases emissions) should be investigated.

1. Introduction

Freshwater resources are currently under great pressure all over the world due to many factors: climate change, population growth, higher standards of living, increased industrialization and widespread urbanization [1]. Water consumption grew twice as fast as population in the last century [2], and nearly half of the global population already live in areas that are potentially scarce in water at least one month per year [3]. The industrial sector accounts for approximately 19% of the total water withdrawals [4], and the construction industry is among the main users. Urbanization boosted, indeed, the demand for construction materials [5], with concrete reaching an annual production of more than 32 Gt in 2017 [6]. Besides the large demand for natural aggregates, concrete production also requires a lot of water. For instance, a standard concrete batching plant withdraws on average 100 m³ of water each day just for the mixing process [7]. However, concrete demand for water goes well beyond this process. Water is required to process all the raw materials and to produce the energy and the fuels used along the concrete production chain [8]. However, inventory data for water demand throughout the life cycle of concrete are limited and inconsistent [9]. Miller et al. tried to estimate the global amount of water consumed to



produce concrete at a global scale and concluded that, on a cradle to gate analysis, concrete production was responsible for a global water consumption of 16.6 Gm³ in 2012, equivalent to the annual domestic use of 145 million US residents [10].

To avoid the corrosion of the steel rebars used in reinforced concrete structures, mixing water must be free of chlorides and therefore, the use of seawater is forbidden and freshwater is currently used [11]. However, the use of reinforcement elements resistant to corrosion (e.g. stainless steel, glass fibre reinforced polymers) has been investigated over the past few years, opening up the opportunity to the use of alternative types of water. For instance, results of the SEACON project showed that the properties of concrete could be preserved and even improved when seawater was used in the mixing process if reinforcing elements resistant to corrosion were used [12]. Moreover, using rebar that would extend the durability of the structure could also reduce the life cycle environmental impacts [13] and the life cycle costs of the structure [14]. Nevertheless, the actual implications of using seawater and, possibly, chloride contaminated aggregates on the Water Footprint (WF) of concrete produced in a specific geographic context were not investigated.

The goals of the study were: (1) to assess the life cycle water consumption and the WF of a generic concrete mix produced in Italy, identifying the most impacting stages of the life cycle, and (2) to assess the variation in the WF if seawater was used instead of freshwater in the mixing process and marine aggregates were included in the mix in place of land-won aggregates. To reach this goal, the WF of the different concrete mixes was evaluated with a GIS-based approach considering both the direct and indirect water consumption in the different life cycle stages of the production of concrete.

2. Materials and methods

The WF of the different concrete mixes was assessed following the ISO 14046 guidelines, which provide a metric to assess the potential impacts associated to the life cycle use of water for an activity [15]. The methodological steps, in line with the standardized life cycle assessment procedure, are presented in the following sections.

2.1. Goal and scope definition

The goal of the analysis was to assess the water footprint of a generic concrete produced in Italy and to investigate whether the use of seawater and marine aggregates could reduce it. Hence, three different mix designs were compared: 1) concrete with Land-won Aggregates (LA) mixed with Fresh-Water (FW), representing the base case scenario and referred to as “LAFW” in the analysis; 2) concrete with Land-won Aggregates mixed with Sea-Water (SW), referred to as “LASW”; and 3) concrete with Marine Aggregates (MA) mixed with Sea-Water, referred to as “MASW”.

2.1.1. Declared unit. The declared unit was one cubic metre of unreinforced fresh generic concrete delivered to the construction site. Except for the type of aggregates (land-won or marine) and mixing water (freshwater or seawater), the same concrete mix was used for all the scenarios. Recipe for the mix (i.e. 200 kg of Portland cement, 1280 kg of gravel, 720 kg of sand and 170 litres of water) was taken from the Ecoinvent database [16] and represents a general unreinforced concrete. All mixes were assumed to have the same mechanical properties and service life.

2.1.2. System boundaries. The approach of the study was from cradle-to-gate, where the gate of the study was the construction site. Transportation to the construction site (i.e. stage A4 according to ISO 14046) was included in the analysis. The different unit processes considered for the analysis and their relative inputs of direct water are illustrated in ‘figure 1’. Direct water refers to the water consumed in a specific process (e.g. water for mixing concrete). Although the component was not shown in the figure, indirect water (i.e. water consumed in preceding processes such as the one consumed in the generation of energy used to mix concrete) was also included in the assessment.

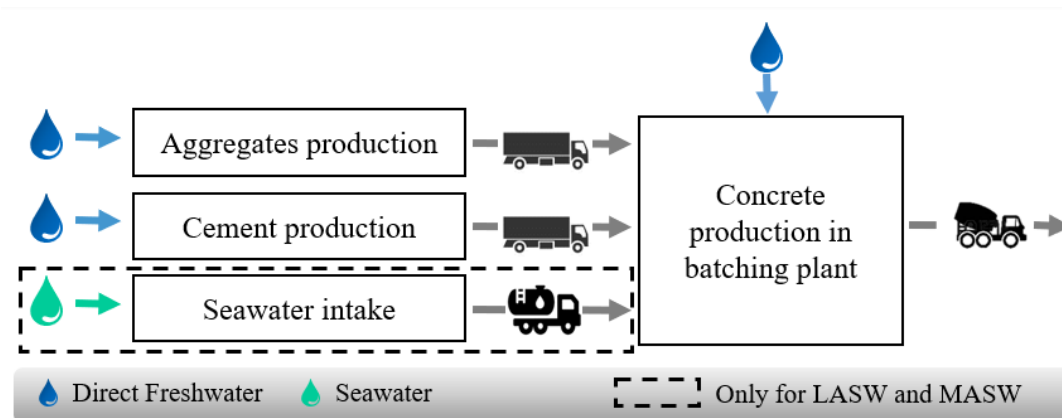


Figure 1. Unit processes considered in the study and their relative direct inputs of water.

2.1.3. Geography. Three different Italian regions (i.e. Abruzzo, Eastern Sicily and Lombardy) were considered for the analysis to investigate the influence of the geographical context on the WF. In fact, the three regions (in the central, southern and northern part of the country respectively) differ in terms of climate, freshwater availability, distance from the sea and type of quarries.

2.2. Life Cycle Inventory (LCI)

Different studies, databases and tools were used for the LCI: studies available in the scientific literature and the Ecoinvent database [16] were used as sources of secondary data; ArcGIS was used for the geolocation of quarries, cement factories, batching plants and seawater intake facilities; finally, the Distance Matrix API of Google was used to calculate the road distances between different points. The electricity consumed in quarries, cement factories and batching plants was modelled using the Italian electricity mix. A focus on the inventory for aggregates and water considered in the different scenarios is presented in the next sections. As for the quality of the data, primary data were collected for energy consumption and water withdrawals in a land quarry and a in a concrete batching plant, while secondary data were used for the other unit processes.

2.2.1. Aggregates. Aggregates, in Italy, are sourced from three different types of land quarries: wet, dry, and rock quarries. Wet quarries are open-pit mines characterized by the presence of a lake, formed when the excavations of sand and gravel penetrates the aquifer's water table. Conversely, in dry quarries the excavation process never reaches the water table. Finally, aggregates from rock quarries are produced from blasting and crushing rocks in mountainous areas. A hypothetical scenario where marine aggregates were used instead of land-won aggregates was also considered in the present study. Although the extraction of aggregates from the seabed is not currently practiced in Italy, this activity is common in other European countries such as the UK and the Netherlands [17]. For this scenario, aggregates were assumed to be dredged from the seabed off the Italian coast and transported by ship to the shore.

In wet quarries, water is used to wash the aggregates and the machinery on site. Aggregates are washed to separate the different sizes, while machineries are washed for productivity reasons. Although not directly used, freshwater is consumed in quarries due to evaporation. Water evaporates not only during the washing process, but also from the extracted aggregates (before and after washing) and from the quarry lake. If aggregates were not quarried, the evaporating water would remain in the aquifer and it would be available for other purposes. For this reason, evaporating water was included in the assessment. On the other hand, not all the water used to wash the aggregates and the machineries is consumed: most of it, in fact, either leaches back to the aquifer or it is conveyed to settling tanks, where silt deposits and decanted water is re-used for washing. For this reason, the only water that is actually

consumed in the washing process is that which is adsorbed by the aggregates or that evaporates. Based on a previous study, the amount of evaporating water was assumed to be 10% of the withdrawn water [18]. As for the water evaporating from the quarry lake, it was calculated using the Visentini formulas, which correlate the evaporation rate from small water surface to the average temperature and the elevation [19]. A wet quarry located in Northern Italy was used as reference case study, and the annual evaporation from the quarry lake was then multiplied by the surface of the lake and the rate was divided by the annual production of the quarry in order to allocate the amount of evaporated water to the produced aggregates.

Water is used to wash aggregates and machineries in dry quarries too. However, since no lake is present in this case and water used for washing is collected and reused for the same purpose, the only water consumed is the one adsorbed by the aggregates or the one evaporating during the activity. Primary data collected by Rigamonti et al. were considered in this case [20].

In rock quarries, aggregates are not washed since there are not fine particles (i.e. silt) to be removed. Nevertheless, water is consumed to control dust and to wash machinery. Data were collected from another Italian study investigating this type of quarry [21]. Decanted harvested rainwater and new freshwater withdrawn from the well were used in the quarry; however, since not enough information was available on the amount of harvested rainwater, only the withdrawn component was considered.

Finally, in case of off-shore extractions, it was assumed that marine aggregates were washed with seawater to remove the fine particles and that no additional washing was required to remove the chlorides contamination. Therefore, direct consumption of freshwater was considered null in this case.

2.2.2. Batching plant. Primary data were collected for water consumed at the batching plant: total direct consumption was equal to 0.50 m³ per cubic meter of fresh concrete, split between the water for mixing (equal to 0.17 m³ based on the Ecoinvent recipe) and the one for washing the truck mixers and the area. For the base case scenario, water for mixing was assumed to be withdrawn from a well located at the concrete mixing plant. On the other hand, seawater was assumed to be collected from an open intake facility on the coast and then transported by truck to the concrete mixing plants.

2.2.3. Cement plant. Primary data from one of the main Italian cement manufacturers were used for the study and 0.24 m³ of FW resulted to be used on average per metric ton of cement, mainly for gas conditioning and cooling activities.

2.2.4. Geolocation, distances and transports. Location of the active quarries in the different regions was retrieved from the official regional websites while location of batching plants and cement factories were provided, respectively, by the Italian Technical Economic Association for Ready-Mixed Concrete [22] and the Italian Association of Cement manufactures [23]. Coordinates of each plant and quarry were then imported to ArcGIS and, for each batching plant, it was assumed that cement was supplied from the closest producer and that aggregates were sourced in equal amounts from the closest four quarries. Finally, fresh concrete was assumed to be transported for 10 km with a truck mixer to reach the construction site [24].

Seawater intake facilities and marine aggregates extraction site were assumed to be located along the coastline, at a minimal linear distance to each batching plant. SW was considered to be transported by tankers from the intake facility to the concrete batching plant.

2.3. Life Cycle Impact Assessment

The AWARE method, developed by WULCA, was used for the impact assessment [25]. The AWARE characterization factors account for the Available Water Remaining in a watershed after the demand of humans and aquatic ecosystems is met. The metric provides characterization factors both at the river basin scale and aggregated at national level. In the present study, basin scale factors were used for direct water consumptions, while aggregated national factors were considered for the indirect uses.

Characterization factors were then imported to ArcGIS and applied to the different plants based on their location.

3. Results and discussion

The actual amount of freshwater consumed to produce 1 m³ of concrete in Italy and the water footprint for the different mixes assessed with the AWARE method are both presented in this section.

3.1. Water consumption

Direct and indirect freshwater consumption for each process unit are listed in ‘table 1’, where all the numbers are referred to the declared unit in the base case scenario (i.e. 1 m³ of fresh concrete delivered to the construction site). An average distance was considered for transportation from the quarry and the cement plants to the concrete mixing facility. Water consumption to produce 1 m³ of fresh concrete ranged between 1.7 and 5.5 m³, according to the type of aggregate used in the mix. The minimum value corresponds to concrete containing aggregates from a rock quarry, while the maximum is referred to the case with aggregates from a wet quarry. The high value of direct consumption for the wet quarry was due to a large extent (i.e. 94%) to the water evaporated from the quarry lake.

Table 1. Direct, indirect and total freshwater consumption for the base case scenario.

Process unit	Indirect water consumption (m ³ _{water} /m ³ _{concrete})	Direct water consumption (m ³ _{water} /m ³ _{concrete})	Total Water consumption (m ³ _{water} /m ³ _{concrete})
Aggregates production – dry quarry	0.03	1.68	1.71
Aggregates production – wet quarry	0.06	4.49	4.55
Aggregates production – rock quarry	0.04	0.71	0.75
Cement plant	0.30	0.05	0.35
Batching plant	0.05	0.50	0.55
Transport	0.03	0.00	0.03
Declared unit	0.41 - 0.44	1.26 - 5.04	1.65 - 5.48

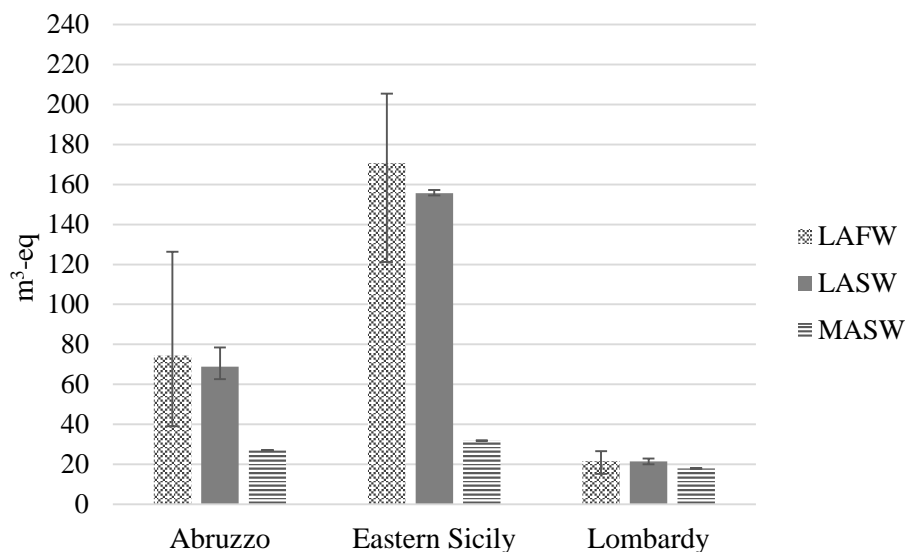
3.2. Water footprint

3.2.1. Base case scenario. WF results for the Italian base case scenario (i.e. LAFW) are summarized in ‘table 2’. In the table, the WF (expressed in world-equivalents m³ of water) of each unit process is reported for the three regions investigated. The *mean* represents the calculated average WF for the concrete produced in the region, while the *range* represents the potential minimum and maximum for each region. Cases where all the aggregates were sourced from only one of the four closest quarries was also included in the analysis. The larger WF in Sicily (up to 300 m³-eq. per m³ produced) was due to the limited remaining available freshwater in the region; conversely, the larger availability of freshwater in Lombardy resulted in lower impacts. The ranges for cement production, batching plant and mixing water are related to the different characterization factors of the river basins where the plants are located. The range for aggregates production depends not only on the characterization factors, but also on the type of quarry. Finally, the range for transportation is related to the transport distance and does not depend on local water availability, since there was no direct water consumption involved in the process. For indirect water, national aggregated characterization factors of the producing countries based on the information available on Ecoinvent datasets were used.

Table 2. Water footprint of each unit process for the base case scenario in the regions investigated.

	Abruzzo			Eastern Sicily			Lombardy		
	Mean (m ³ -eq.)	Range	Share (%)	Mean (m ³ -eq.)	Range	Share (%)	Mean (m ³ -eq.)	Range	Share (%)
Aggregates prod	46	13-98	61	126	49-256	74	10	4-15	46
Cement prod	10	9-11	13	12	12	7	8	8	37
Batching plant	13	7-21	17	16	15-17	9	3	3	12
Mixing water	6	3-10	8	15	14-16	9	< 1	< 1	2
Transport	< 1	< 1	1	1	1	1	< 1	< 1 - 1	3
Declared unit	65	32-141	100	171	91-303	100	21	15-27	100

3.2.2. Alternative scenarios. A comparison of the WF for the different scenarios considered (i.e. LAFW, LASW and MASW) is presented in ‘figure 2’. Error bars indicate the minimum and the maximum WF in the different batching plants. Differently from ‘table 2’, the minimum and maximum considered here do not consider the cases where all the aggregates were sourced from a single supplier. Since the AWARE characterization factor for seawater is null, the WF of the water used for mixing in the LASW and MASW scenarios was only due to its transportation from the coast to the batching plants.

**Figure 2.** Average water footprint for the three scenarios in the regions investigated.

Replacing FW with SW resulted in a reduction of the WF of concrete from less than 2% in Lombardy to 9% in Eastern Sicily. Using MA instead of LA resulted in a further reduction of the WF in almost all the batching plants analyzed. In Abruzzo and Eastern Sicily, the reduction would be extremely significant (i.e. always larger than 45%) thanks to the avoided direct freshwater consumption in areas affected by high water stress. In Lombardy, on the other hand, the WF implications depend on the type of aggregates that would be substituted. Given the long distance from the coast, the benefits of using MA in terms of WF were clear (up to a 36% reduction) only when aggregates from wet quarries were replaced.

4. Conclusions

In the present study, the amount of freshwater consumed to produce 1 m³ of fresh concrete and its WF were assessed for three Italian regions differently affected by water stress. Moreover, the implications on the final WF of substituting land-won aggregates with marine ones and using seawater instead of freshwater for mixing the concrete were investigated. The following conclusions could be drawn:

- Aggregates production proved to be the determining parameter on the final overall freshwater consumption, while water used to mix the concrete resulted to be only a fraction of all the freshwater consumed along the production chain (i.e. from a minimum of less than 2% to a maximum of 12%). Freshwater evaporating from quarry lakes could considerably increase the amount of water consumed in case aggregates from wet quarries were used, with a contribution that could reach 4.2 m³ per m³ of concrete (i.e. up to 77% of the total consumption). Moreover, cement production and water consumed in batching plants in addition to that used for mixing, contribute significantly to the overall consumption. On the other hand, the indirect water consumed to transport the different materials resulted to be trivial.
- Similarly, water physically incorporated in the fresh concrete was only partially responsible for its WF (i.e. 8 to 9% of the total WF in areas affected by high water stress and 2% in Lombardy, where the direct water consumptions are less impacting). Accordingly, using seawater could reduce the WF of concrete up to 12% in Eastern Sicily and would negligibly affect the WF in Lombardy.
- On the other hand, replacing land-won aggregates with the marine counterpart could reduce to a great extent the pressure of concrete on freshwater availability in areas affected by water stress, leaving freshwater available for human consumption. In Eastern Sicily, for instance, using marine aggregates and seawater could reduce the WF up to 80%. However, if aggregates need to be transported for a long distance and the area has a large availability of freshwater, using marine aggregates might be detrimental for the WF.

5. Further investigations

The present study was a first attempt to assess the implications of using alternative sources of water and aggregates on the WF of concrete. Even though the study showed positive outcomes, before promoting their use further research is necessary to investigate a possible burden shifting (e.g. implications on greenhouse gas emissions and aquatic ecosystems, which fell outside the scope of the present work). Moreover, the durability of the concrete designs and the water consumption in the manufacturing of the reinforcing elements should be included in the analysis to extend the present results to the whole life cycle of the building material. Furthermore, some assumptions made for the present analysis should be further revised to improve the robustness of the study. For instance, water evaporating from the quarry lake resulted to be a decisive parameter in the WF of concrete in regions with wet quarries. However, the dimension of the lake, the temperature in the region, the productivity and the service life of the quarry would greatly affect the amount of evaporating freshwater that should be allocated to the aggregates. Finally, an additional sensitivity analysis considering different strengths and water-to-binder ratios for concrete should be performed to investigate variations in the role that water for mixing and mixture components might play in the overall WF of the material.

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