Procedia CIRP 90 (2020) 280–284

Contents lists available at ScienceDirect

Procedia CIRP

journal homepage: www.elsevier.com/locate/procir

Environmental evaluation of treated tailing as Supplementary Cementitious Material

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ARTICLE INFO

Keywords:
Copper Treated Tailings
Enviromental Impact
Cementitious Mixes
Supplementary Cementitious Materials

ABSTRACT

Copper treated tailings (TT) have been studied as a supplementary cementitious material from a mechanical performance point of view. Nevertheless, treatments on tailings introduces impacts that need to be considered when evaluating the environmental performances. This Life Cycle Assessment (LCA) study focusses on the use in concrete mixes of TT. Mixes were compared to concrete mixes without TT for three scenarios: equivalent compressive strength with same water-to-cementitious ratio, maximum compressive strength, and minimum allowable strength. Results show that in case of concrete mixes with higher mechanical performance, environmental impact indicators show better results than those of concrete mixes without tailings.

1. Introduction

Cement production represents between 8-10% of anthropogenic emissions of carbon dioxide in the world (Robayo-Salazar et al., 2018): the manufacturing of 1 tonne of cement is roughly equivalent to the release of 1 tonne of CO2. Because of the impact of the production of this material, the use of Supplementary Cementitious Materials (SCMs) has been widely explored in the last years (Lothenbach et al., Dec. 2011, Fan and Miller, Apr. 2018). Natural pozzolans (Fan and Miller, Apr. 2018), zeolites (Küçükyıldırım and Uzal, Dec. 2014), calcined clays (Taylor-Lange et al., May 2015) and sewage sludge (Oliva et al., Jun. 2019) have been gaining interest as new SCMs as well as slags (Yang et al., Apr. 2017) and tailings (Choi et al., Jul. 2009). Copper tailing has been studied as SCM with generally poor performance results (Onuaguluchi and Eren, 2015, Thomas et al., Nov. 2013) due to high crystallinity and particle size not compatible with hydration of cement. To improve performance of tailings from different sources in Chile as SCM, mechanical and thermal treatments have been applied, allowing the use of more material as replacement of cement (Vargas and Lopez, May 2018).

Life Cycle Assessment (LCA) has been used to calculate the potential environmental impacts of mixes with different SCMs, such as fly ash (Celik et al., 2015), rice husk ash (Gursel et al., 2016) or sewage sludge (Nakic, Oct. 2018). Unfortunately, divergent data related with the benefit of the use of SCMs, different approaches to analyse concrete mixes with and without SCM and huge differences in the scope of research can be found between different studies (Damineli et al., Sep. 2010, Yang et al., 2015). Moreover, previous studies consider the impact of the inclusion of the SCMs to be negligible due to the consideration that most of those materials are wastes from other industry. In the case of treated tailings, Waste Framework Directive 2008/98/EC (Directive, 2008) and ISO 14040 and ISO 14044 standards recommend considering it as a waste, because of its nature as an unintended residue. Nevertheless, the use of energy, processes to produce this SCM and transportation need to be taken into account to estimate the environmental impact of the use of this material as a replacement of cement.

The aim of this research is to evaluate the potential environmental impacts of the use of treated tailings (TT) as SCMs, at different replacement levels according to specific performance levels in a concrete made for the Chilean context. Moreover, this research wants to determine whether the use of TT improves the environmental indicators of concrete or, due to the requirement of mechanical and thermal treatments, generates an additional environmental burden.

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https://doi.org/10.1016/j.procir.2020.02.008

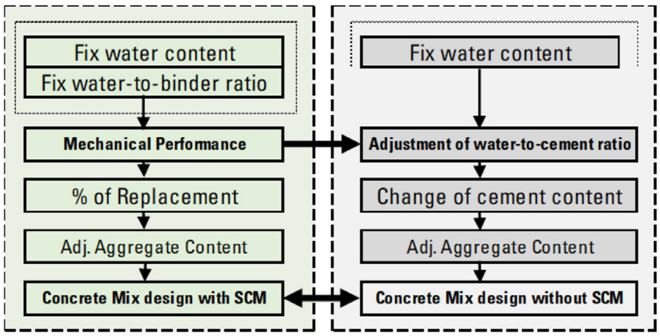

Fig. 1. Flow chart of procedure for the selection of concrete mixes for a proper comparison.

2. Methodology

2.1. Goal and scope definition

The aim of this LCA is to evaluate the environmental benefits of the use of TT as SCM into concrete mixes, based on tailings and concrete production in Chile. The Functional Unit (FU) is defined as the production of 1 cubic meter (m3) of concrete with a specific mechanical performance, within three proposed scenarios (explained later).

The system boundaries consider the processes of the production of aggregates, cement, water, extraction of tailings from the tailing dam, and production of the TT, until the concrete leaves the concrete mix facility, in a cradle-to-gate model system. The avoided process of the tailing disposal is also considered in the system boundaries. As for modelling, the SimaPro 8.3 software was used to perform the LCA analysis. The characterization method chosen to assess the environmental impact was ReCiPe v1.12 (H) since there is no specific method for the Chilean context and due to its global scope.

For this study, two tailings were collected: one from an ongoing production mine (OP1) and the other one from an abandoned tailing deposit (LS5). Both tailings were used on a previous study (Vargas and Lopez, May 2018). Grinding for 30 minutes will be used as mechanical treatment and calcination was set at 600°C for OP1 tailing and 700°C for LS5 tailing. Energy requirements for calcination and grinding as well as mass losses and emissions were considered in the modelling, according to data collected from laboratory measurements.

The mechanical performance included in the FU is the compressive strength. Nevertheless, to make comparison more accurate, some considerations need to be exposed:

- To compare only the effect of the use of the TT, water content will be maintained at the same level for all the mixes. In the same line, no additives are considered into the mixes. Water-to-binder ratio by mass is fixed to 0.5 on TT mixes.
- Binder content is the same for the mixes with TT.
- To compare mixes with the same performance level (compressive strength), cement content was changed in concrete mixes without TT and samples were prepared changing the water-to-binder ratio but maintaining the water content to obtain the water-to-binder ratio versus mechanical performance curve.

Fig. 1 shows a chart of how this procedure is executed.

The focus with this proposed method is to make comparisons using the mix design as a tool and the properties of the materials as an input, considering in all the mixes the mechanical performance of the TT and cement. With the exposed considerations, three scenarios were proposed for each tailing (Table 1):

1. Equivalent Compressive Strength: concrete at 0.5 water-to-binder ratio without TT is compared with a mix with TT with the same mechanical performance level (achievable with a certain replacement level at the same water-to-cementitious ratio).
2. Maximum Compressive Strength: the mix with the higher mechanical performance, at a certain replacement level by TT, is compared with a concrete mix without TT. To obtain the same mechanical performance, water-to-binder ratio is changed.
3. Minimum Allowable Compressive Strength: defined as the minimum compressive strength that allows a minimum level of resistance to chemical attacks (chloride and carbonation) as defined by European and Chilean standards, i.e. 20 Mpa (I. O. for Standardization, ISO 14040 2016, I. O. for Standardization, ISO 14040 2013). This represents also the maximum replacement level for these mixes.

The system was extended for the mixes without TT changing the amount of cement, maintaining the amount of water. Table 1 shows the mix design for each sample selected for the LCA. It also shows the replacement level and the compressive strength for each mix.

2.2. Inventory data

Primary data was used for the energy requirements and emissions of the production of the TT. LS5 and OP1 tailings were collected at 700 km and 100 km approximately far from Santiago, the main point of consumption of concrete in the country. Due to the absence of a national database for Chile, data from ecoinvent 3.1 database were selected as base and modified with specific Chilean data for all products and processes. Energy production matrix for Chile was used and datasets were adjusted properly.

More in detail, data about energy and emissions for cement production was obtained from an ecoinvent dataset related to the United States, adjusted and complemented with information obtained from Chilean producers related with distances, types of transportation, type of production and energy. Clinker was considered as imported due to actual behaviour of the market and that most of the Chilean cement industry produces pozzolanic cement (I. O. for Standardization, ISO 14040 2018) instead of the Portland cement used for this research. Data for aggregates was obtained from ecoinvent database and adjusted to the type of production in Chile: mining and river embankment production. Changes were made on type of production, transportation distances, and energy requirements for each of both systems. All transportation inside the country was modelled by truck. A sensitivity analysis was made on the transportation distance of the TT. In fact, the SCM can be consumed in a big consumption site, as is modelled in the baseline scenario (700 km for LS5, 100 km for OP1); but also, it can be consumed on site for the mining project itself, or nearby mining sites. Extraction and handling of the tailings were modelled based on information obtained from ecoinvent database. Energy required to produce TT is equivalent to 0.836 kWh per kg of treated OP1 and 0.951 kWh per kg of treated LS5 tailing. Water released to the air is 0.065 kg per kg of treated OP1 and 0.069 kg per kg of treated LS5. Release of CO_2 due to decarboxylation of carbonates represents 0.014 per kg of treated OP1 and 0.044 per kg of treated LS5.

3. Results

The use of TT shows equal or lower environmental impacts for most of the impact categories (with the exception of fine particle matter and terrestrial acidification). Fig. 2 shows for example the relative comparison among the analysed mixes in scenario 1 for five impact indicators. A difference of less than 10% can be considered not significant due to uncertainty in the study. The benefit

Table 1
Mix design for LCA, replacement level and mechanical performance for the three scenarios (BC: base case for each scenario made with concrete without tailing; OP: concrete mix with OP1 tailing; LS: concrete mix with LS5 tailing; number represent the compressive strength).

	Equivalent CompressiveStrength			Maximum CompressiveStrength				Minimum Allowable CompressiveStrength		
Quantity (kg)	BC-34	OP-34	LS-34	BC-41	OP-41	BC-37	LS-37	BC-20	OP-20	LS-20
Cement	356	257	305	420	285	378	320	261	200	214
Treated Tailing		99	51		71		36		156	142
Coarse Aggregate	958	957	957	958	994	958	966	958	916	958
Fine Aggregate	930	928	928	858	892	911	920	1011	966	919
Water	178	178	178	178	178	178	178	178	178	178
Replacement Level		27.8 %	14.4 %		20 %		10 %		43.9 %	40 %
Compressive Strength (MPa)	34.5	34.5	34.5	41.5	41.5	36.6	36.6	20.6	20.6	20.6

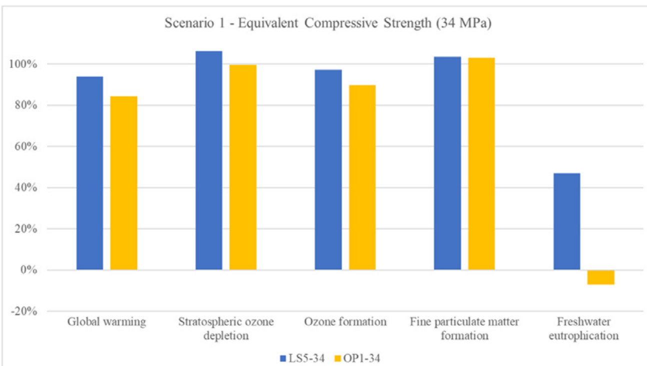

Fig. 2. Relative comparison among some of the impact indicators of the analysed mixes (concrete mix without treated tailing is 100%). Scenario 1: equivalent compressive strength.

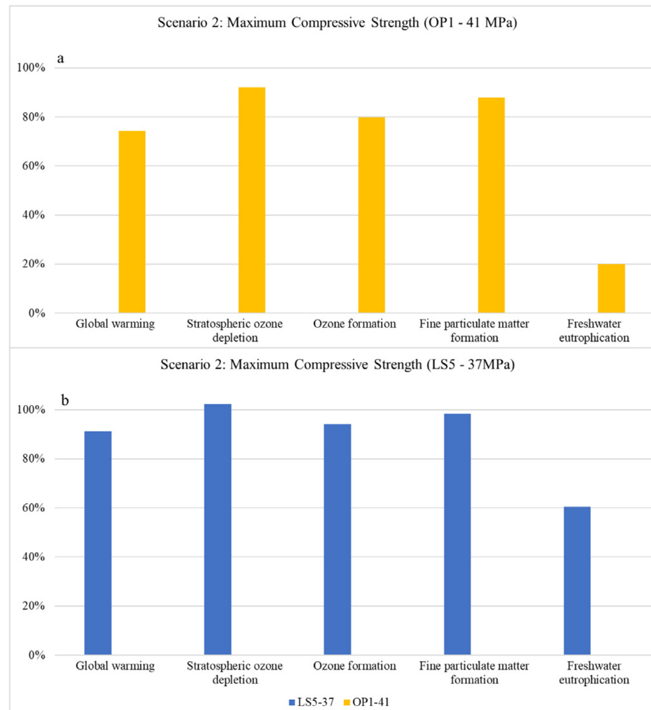

Fig. 3. Relative comparison among some of the impact indicators of the analysed mixes (concrete mix without treated tailing is 100%). Scenario 2: maximum compressive strength. a. Mix with OP1 TT vs mix without TT. b. Mix with LS5 TT vs mix without TT.

with the use of OP1 TT can be seen for this scenario, with impacts in the range between 80-90% of those of the concrete mix without TT for categories such as global warming and ozone formation, while in stratospheric ozone depletion or particle matter formation the two mixes show similar results. On the contrary, the higher temperature needed to obtain the TT from the LS5 tailing generates similar results for all impact categories compared with the base case for this scenario. The avoided disposal of both tailings generates an important benefit in the freshwater eutrophication indicator due to avoided leaching, because of elements that are entrapped into the cementitious matrix (Guo et al., May 2017). This effect is more relevant at higher replacement level (i.e. when using OP1 TT).

Fig. 3 shows that in scenario 2 the environmental benefits of the use of treated tailing are more relevant. This can be explained by the fact that to obtain the same performance, cement needs to be added to the mixes without TT, which is the most relevant material in contribution to the environmental indicators. Also, the addition of TT is not so high (OP1 replacement level of 20% and LS1 replacement level of 10%) to be important as contribution to the indicators. In this case, due to differences in the performance of the tailings as SCM, OP1 TT has a better mechanical performance than LS1 TT (41 Mpa versus 36 Mpa), allowing mixes with OP1 TT to perform between 10% and 20% better than mixes with LS5 TT when compared with the case without TT. Note that the comparison between the mixes with TT is not possible in this case because of the different mechanical performance level.

In the case of mixes with lower mechanical performance (scenario 3) (Fig. 4), impact indicators of categories such as global warming, stratospheric ozone depletion, particle matter formation, and terrestrial acidification are quite higher than those for a mix without TT. Indeed, there is a decrease in the environmental performance of LS5 TT mix of this scenario compared with mixes with LS5 TT with lower replacement levels, due to higher energy requirements for the treatments and transportation of tailings, which is not countered by the less cement content. For the OP1 TT mix, with a 43.9% replacement level, which is equivalent to replace each kilogram of cement by 2.55 kilograms of treated tailing, the environmental impacts of the production of TT for the mix are higher than those associated with the cement production. Therefore, the use of TT in this scenario (high replacement levels and lower mechanical performance) implies an increase of the environmental impacts. On the contrary, the indicator for freshwater eutrophication is slightly better for mixes with TT, due to the benefit of the avoided deposit of tailings.

Changes in the distance of consumption of the TT are not very relevant. Fig. 5 shows the increase that appears in each indicator for four relevant impact categories when adding 100 km of transportation to the baseline considered in the system, comparing each scenario mix with its own base case mix without TT. It can be seen that transportation has an impact of less than 3.5% in all impact categories, also due to the low levels of use of each TT (156 kg as maximum, approx. 0.05 m3) compared with the total volume of materials for each mix.

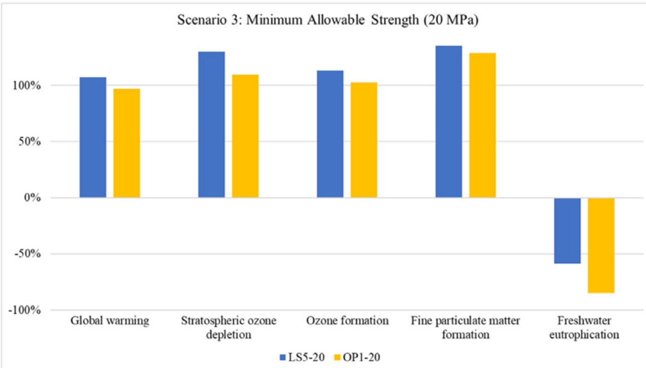

Fig. 4. Relative comparison among some of the impact indicators of the analysed mixes (concrete mix without treated tailing is 100%). Scenario 3: minimum allowable compressive strength.

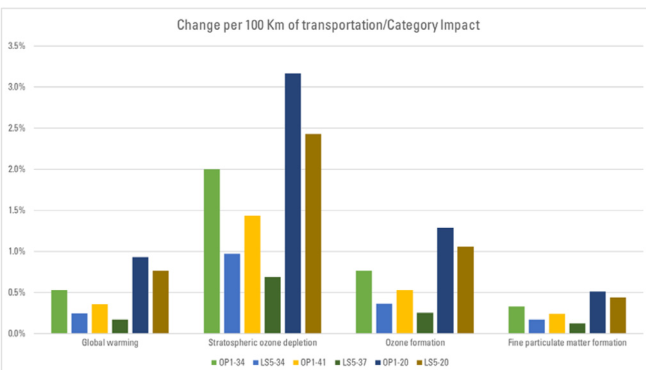

Fig. 5. Percentage increase on each indicator per 100 km of transportation of TT added to the system on four selected impact category indicators.

4. Conclusions and future work

Two TT from Chile were chosen to compare, from an environmental point of view, their use as SCM with concrete without TT at the same performance level, where all performances are measured as compressive strength. Three different scenarios were considered: equivalent performance level, maximum mechanical performance and minimum allowable performance level. Results show that the environmental indicators are highly dependent on the characteristics of each tailing, in particular their chemical and mechanical characteristics that influence the processes and temperatures needed to obtain the SCM.

At a higher mechanical performance level of the mix with TT, the LCA show better results than mixes without SCM. In the case of tailings mixes with poor performance levels, due to the low amount of cement that is necessary to obtain the same compressive strength, the environmental benefits of the use of TT disappear and a decrease in the environmental performance of the concrete mix with TT are registered.

In general, due to higher performance level, and due to a lower distance of transportation, OP1 appears as the most attractive tailing to work for as SCM. But due to high heterogeneity of tailings in chemical composition and performance (Vargas and Lopez, May 2018), an ad-hoc evaluation is necessary for each tailing.

In this study a new focus has been proposed on the way that comparisons should be performed to decide whether a mix with SCM is environmentally better than a mix without SCM, changing the binder content and avoiding transformations or calculations ex-post. This permits direct comparisons for mixes with SCM for specific levels of performance and can be a powerful tool to decide the level of replacement and performance at what a single SCM can be used on a green concrete mix. This is especially useful for SCM that need extensive processing and also for materials with low performance level as cement replacement, but that can work on mixes where a specific performance is not a requirement, such as low mechanical performance mixes or provisory structures, where durability is not an issue.

From the results obtained in this LCA study, it can be stated that:

- The use of TT as replacement of cement in concrete mixes can be a promissory way to reduce the use of cement and reduce the impact of the deposit of tailings. Nevertheless, studies need to be carried out to analyse and determine what would be the best use and replacement level of those mixes in the form of a mixture design for concrete to improve mechanical and environmental performance.
- It is not evident whether a tailing will produce an environmental benefit by its use as replacement of cement or no. Calculations on the effect of the treatment of tailings and the performance of the mixes are relevant.

Considering that the data used for the modelling of the treatments are primary data but acquired at a laboratory level, upscaling the processes could allow to reduce the environmental impacts of the treatments of the tailings. Also, due to lack of information for the Chilean context, some processes were modelled based on global models and later modified. Other performances variables could be considered into future work: durability is a main issue, but also workability and rheological properties can be considered.

Declaration of Conflict Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Felipe Vargas: Conceptualization, Methodology, Writing - original draft, Investigation, Formal analysis. **Lucia Rigamonti:** Supervision, Writing - review & editing, Validation.

Acknowledgements

This project was supported by the doctoral scholarships CONICYT-PCHA/Doctorado Nacional/2015–21150946.

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