Chapter

Different Approaches to Develop More Sustainable Concrete Alternatives

Mauricio Pradena and Andrés César

Abstract

As important as it is, sustainability related with the concrete material is more than reducing the amount of cement in concrete mixes. In effect, there can be other types of contributions to a sustainable development using this fundamental material. The purpose of this book chapter is to analyse some of these approaches, in particular, concrete durability, reducing the amount of required concrete (and then cement) through innovative structural design, and reducing the amount of aggregates used in the concrete material. More specifically, examples and results obtained in Chile with biological self-healing concrete, thinner concrete pavements and concrete with industrial and domestic waste as partial aggregate replacement are included in the chapter. Due to its importance, the geo-dependency of the concrete material is addressed as well.

Keywords: sustainability, concrete with waste, concrete durability, thinner concrete pavements, self-healing concrete, life-cycle

1. Introduction

Concrete is the most widely used building material due to its strength, adaptability, low maintenance requirements during the lifetime of structures, and the economic and extended accessibility of its components [1], which makes it very difficult to replace in many infrastructure applications [2]. In fact, globally, concrete production is estimated at approximately 25 billion tonnes per year [3].

However, a relevant challenge is the amount of harmful emissions produced by concrete [4]. Actually, cement manufacturing and concrete production account for 6–9% of global man-made CO2 [5, 6]. Furthermore, by 2050, this value is projected to increase by 4% due to an increase of 12–23% in cement consumption [7]. Cement production generates, as well, high NOx and SOx emissions, which contribute to the development of acid rain, deterioration of public health and global climate change [8, 9].

Additionally, the high demand for natural aggregates used in the concrete mix generates a loss of vegetation and fauna, a decrease in air quality due to emissions of particulate matter, loss of fertile soil, risks of contamination of groundwater and deterioration of the life quality of people living near the extraction sites [10]. Furthermore, the extraction of aggregates can cause morphological alterations in the shape of the channel, bottom and banks, which has repercussions upstream through rebound erosion, generating a considerable increase in the velocity and shear stress of the flow and favouring the erosion processes in the riverbed [11].

The negative impacts related with the concrete material can be minimised by adopting a sustainable approach [12], where sustainability is understood as meeting the needs of the present without compromising the ability of future generations to meet their own needs [13]. In this context, sustainable engineering implies not only the use of sustainable materials, but a sustainable engineering system, where different engineering stages and processes can include factors such as reduction of environmental impacts, economic accessibility and access to the engineering solution regardless of the geographical location [14]. Therefore, from this holistic approach, the result is an alternative with ae technical, environmental, economic and social balance [15].

As important as it is, sustainability related with the concrete material is more than reducing the amount of cement in concrete mixes. Actually, sustainable characteristics have been reported by optimising the design of structures [16–18], replacing natural aggregate with different types of waste such as recycled crushed concrete, marble waste [19] or waste foundry sand [20] and incorporating non-traditional materials such as fibres [21, 22], biological material [23], hazardous waste material [24] or nanomaterials into concrete [25].

The objective of this book chapter is to analyse different types of contributions to a sustainable development using the concrete material. Although some examples are mentioned for the case of reducing the amount of cement directly in the concrete mixes, the analysis is focussed on the other approaches presented in Section 3 and analysed in Section 4 using different examples, most of them proposed from the concrete laboratory of the University of Concepción, Chile. Related with this, Section 2 presents the fundamental concept of geo-dependency, which is directly related with the development of practical and useful sustainable concrete alternatives.

2. Geo-dependency of the concrete material

Concrete is composed of local raw materials. This characteristic is one of the explanatory factors of the massive use of concrete in the construction industry. However, this geo-dependency means that the specific types of cement used, the aggregates and the water influence the final behaviour of the concrete.

The aggregates represent between 70% and 80% of the volume of concrete and almost 90% of the total concrete weight. Therefore, the shape, surface roughness and mineralogical type of the aggregate plays a relevant role in defining the thermal and mechanical properties of the concrete [26].

Similarly, the composition of the cement and the fineness with which it is ground in its manufacture have significant effects on the concrete behaviour. For instance, in the heat of hydration, which can have effects on the durability and service life of concrete structures [27, 28].

Furthermore, the performance of concrete in service is also influenced by conditions of the site environment such as levels of chlorides, sulphates, humidity, pH, CO_2 and thermal amplitude.

Hence, the concrete is a geo-dependent material because its functional performance is determined by the raw materials used in its manufacture and the local construction conditions. In this way, concrete mixes produced in two different regions of the planet are different, even though they can have the same strength.

Geo-dependence is also crucial when dealing with waste materials incorporated in concrete, especially because these alternative solutions must be practical and feasible to implement in order to effectively reuse the waste [29]. Therefore, they must be feasible not only from a technical point of view, but from an economic perspective, as well, including all associated costs.

In effect, if the final purpose is to efficiently reuse waste by incorporating it into concrete, geo-dependency leads to an evaluation of the performance of these solutions according to the local context. In this way, the results obtained contribute to the optimal use of waste and then to sustainable development, which can be adopted in other regions as well. For instance, regions with similarities, that can be in the type of cement composition, cement substitute materials and/or characteristics of the aggregates.

3. Sustainable approaches related with the concrete material

3.1 Approaches based on the phases of the concrete material life-cycle

The methodology to assess the environmental impact of a material, includes the calculation of the related emissions generated and energy required in the different phases of the material life-cycle, i.e. from the extraction of raw materials to the end of the first life. Therefore, the use of the life-cycle phases of the concrete material results especially useful to analyse different contributions to more sustainable alternatives of this massive use material.

Evaluating the energy consumption and generated emissions of material alternatives allows to quantify sustainable benefits at different stages of the life-cycle. For instance, in the material production stage, alternatives can be generated to reduce the amount of cement and natural aggregates used in the concrete mix. And in the product manufacture stage, benefits can be achieved by implementing optimised design and construction procedures that reduce the amount of concrete or alternatives with less demanding maintenance interventions, or with better thermal insulation and then less demanding of heating energy. Furthermore, more durable concrete can be produced in such a way that at the end of the first life the material can be reused.

In the present section some of those different approaches are introduced (**Figure 1**).

3.2 Reducing the amount of cement in the concrete mix

An alternative to minimise the harmful emissions generated by concrete is to directly reduce the consumption of cement in the mix. For that purpose, supplementary cementitious materials have been developed to replace part of the required cement [31].

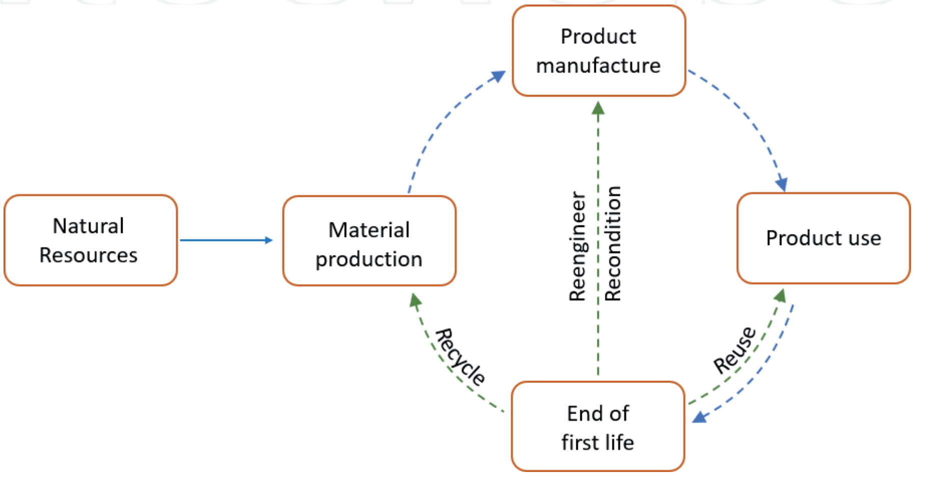

Figure 1.
Material life-cycle [30].

These alternative materials include the reuse of waste such as fly ash, which can replace 15–30% of cement [32–36] and silica fume which replace cement by 5–25% [37, 38]. There are other residues as well that have been used, such as ground granulated blast furnace slag [39], metakaolin [40, 41], sewage sludge ash [42, 43], rice husk ash [44], which can replace up to 20% of cement.

Alkaline activated cements can be used to replace more than 50% of conventional cement [45–48]. This material is a product with cementitious properties generated from the reaction of a powdery material with an aluminosilicic nature and an alkaline agent [49]. Alkaline cements are mainly characterised by low hydration heats, high mechanical performance, good durability against different chemical attacks, often using industrial waste as the only raw material and not requiring high energy consumption compared to the Portland cement manufacturing process [50].

Even a "cementless concrete" can be produced by implementing a sub-group of alkaline-activated materials called geopolymers [50]. In this regard, the main author of this chapter has the experience of design and making geopolymer material with Chilean aggregates in the Microlab TU Delft. The results were optimal, obtaining without problems the design strength.

However, the implementation of the technology of actively alkaline cements and geopolymers requires great care in their production. In addition, the polymerisation reaction is very sensitive to temperature and requires the curing of the geopolymer concrete to be at an elevated temperature under a strictly controlled temperature regime [51, 52]. These aspects coupled with the lack of standardisation of the material make the practical implementation of this technology limited to particular engineering solutions such as the construction of prefabricated structures like sewer pipes and marine members.

3.3 Implementation of optimised designs

Another approach to reduce the environmental impact of concrete is to implement sustainable design features. For instance, optimised structures requiring fewer concrete material to satisfy the in-service demands or optimised structures requiring less conditioning energy during their use phase. Optimisation has been applied in the design of hydraulic structures as dams [16–18]. Actually, Deepika and Suribabu used differential evolution algorithm to find the best optimal shape of a gravity dam reducing 20% the demand of concrete [53].

Similarly, Hashemian proposed a cambered curve beam which requires 20% less concrete than the conventional prismatic beam [54].

Other possibility of optimization is to take better advantage of intrinsic properties of the concrete material in the design of structures. An of example of is the concrete thermal inertia, which is the characteristic of taking a long time to warm up, but, once warm, taking a long time to cool down, and vice versa. This property incorporated in building design can result in structures that maintain a comfortable internal temperature by means of a better interaction with the environment [55, 56]. As a result, a reduction of the conditioning energy over the lifetime of the building is achieved.

3.4 Improving the concrete durability

From a sustainable and technical perspective, the greater the durability of the concrete material, the greater the benefits. Certainly, it is not the same to have a concrete material, for the same application, enduring 15 or 60 years. If the structure has good durability, then it will require less significant interventions and the service life can be extended. In this regard, the ICRI Committee 160 mentions that the most effective sustainability strategy for concrete and masonry structures is to avoid the need of repairing [57].

A particular case is reinforced concrete, where it is very important to avoid or reduce the entrance of atmospheric agents that can corrode the reinforcement [58–60]. This can prevent advanced deterioration and damage, which repair works, require substantial resources. For example, in the UK the annual cost of repairing reinforced concrete structures near coastal areas is £755,000,000 [61]. Similarly, between 1991 and 2001, the cost of corrosion repair of reinforced concrete structures in the United States was $276 million, representing 3.1% of the gross domestic product [62].

In order to prevent corrosion deterioration, it is essential to reduce the formation and propagation of micro-cracking generated by the concrete shrinkage phenomena at early age [60, 63, 64]. As alternatives to limit the micro-cracking and thus increase the concrete durability, Jonkers et al. developed a promising self-healing concrete technology based on the application of mineral produced by bacteria included in the mix [23]. This method allows to repair from inside the material without requiring external agents to activate the process.

Another widely evaluated alternative is the incorporation of fibres in the concrete, which can reduce the number, size and propagation of microcracks [21, 22]. In this case, compared to man-made fibres, natural fibres are less expensive, locally available (in some cases as industrial waste), renewable, lightweight, biodegradable and less energy intensive to produce [65–67].

3.5 Reducing the amount of natural aggregates in the concrete mix

The concrete industry generates a high demand for natural aggregates, due to the massive use of concrete, and the fact that approximately 70% of the volume of this material is composed by aggregates [68]. Uribe mentions that aggregate extraction processes generate loss of vegetation cover and soil [10]. Consequently, the landscape and the habitat of the existing fauna in the area are altered. Moreover, soil fertility and air quality are reduced due to emissions of particulate matter. Therefore, the life quality of the people living near the extraction sites is affected as well.

Another direct impact relates to construction costs. Indeed, as aggregates are a finite resource, they can become scarce, which can increase the cost of acquiring and transporting materials from more distant locations.

Globally, up to 17.5 Gt of aggregates have been consumed annually for concrete manufacturing [69]. In the United States, two billion tonnes of aggregates are produced annually [70]. Similarly, it is estimated that in Chile, aggregate extraction amounts to 7 million 500 thousand cubic metres produced annually, of which five million correspond to gravel and sand [71].

Therefore, in order to preserve natural resources and, at the same time, contributing to solve waste disposal problems, it has been evaluated to replace natural aggregates by different types of waste such as recycled crushed concrete, crushed bricks, recycled glass, rubber, ceramics, marble waste, textile effluent sludge [19], waste foundry sand [20], steel slag [72], copper slag [73], blast furnace slag, ferrochrome slag, class F fly ash, palm oil clinker [68] and various types of plastic waste [74].

4. Examples of sustainable concrete alternatives

4.1 Case studies

Based on life cycle approaches, the concrete laboratory of the Universidad de Concepcion in Chile has made efforts to contribute to the development of technologies that decrease the harmful impact generated by the concrete industry. This section describes these technologies and presents the relevant results of each study.

4.2 Reduction of the amount of cement by means of optimised structural pavement design

Since all the desired objectives and requirements of an engineering structure are specified in the design phase [75], in the case of concrete pavements, the structural design plays an important role in improving the sustainability of the road infrastructure [76]. In this regard, the design method of short slab Jointed Plain Concrete Pavements (JPCP) is a patented alternative that proposes to shorten the slabs size in such a way that there is only one set of wheel loads per slab [77, 78]. Therefore, the traditional configuration where the slab can support the full vehicle load does not occur. The benefits of this design include, as well, a reduced slab curvature. In this way, the pavement thickness can be reduced up to 10 cm [78], which means than less concrete is required, and then the demand of cement, aggregates and water decreases.

Additionally, it is postulated that the primary method of transferring loads between slabs is the aggregate interlock mechanism, and then, dowel bars are not part of the standard design.

These features result in savings of approximately 20% of the construction cost, which makes concrete pavements with optimised geometry a competitive solution compared to asphalt pavements when only construction costs are considered in the analysis, i.e. without life-cycle costs [78]. This is especially relevant in developing countries, where construction costs can be the main limit to the application of more durable pavements with less maintenance intervention requirements than asphalt pavements [79, 80]. In fact, promising experiences with concrete pavements with optimised geometry have been carried out in developing countries such as Chile, Guatemala, Nicaragua and Peru [78, 81–83]. Moreover, evaluations of short slab test sections in the United States indicate that these pavements have the ability to maintain in-service performance similar to traditional concrete pavements up to 51.3 million equivalent axle loads (ESAL) [84].

In order to estimate the benefit of this engineering innovation, the emissions generated in 18 short slab projects and their traditional JPCP equivalents were compared [85]. The assessment was based on environmental management principles and measures the impact on the environment and human health [86, 87]. Furthermore, it is assumed that the design hypotheses are fulfilled and then the in-service performances of both pavement alternatives are equivalent. For this reason, the evaluation is focused from the material procurement stage to the construction phase, which presents differences between the two design philosophies.

The results indicate that, for all cases evaluated, the concrete pavements with optimised geometry generate lower harmful impacts (**Figure 2**). Regarding environmental impacts, all indicators presented reductions above 10%, with global warming, acidification and ozone depletion showing the highest reductions with 33%, 27% and 24%, respectively. In terms of human health impacts, short slab pavements reduce, as well, exposure to carcinogenic, non-carcinogenic and respiratory pollutants by 26%, 23% and 27% respectively.

The reduction in these indicators reflects that concrete pavement with optimised geometry contribute to a more sustainable construction. The visible advantages of short slab pavements are related to their ability to maintain a performance similar to a traditional JPCP while using thinner slabs. This reduction means less cement consumption, which is the main generator of emissions.

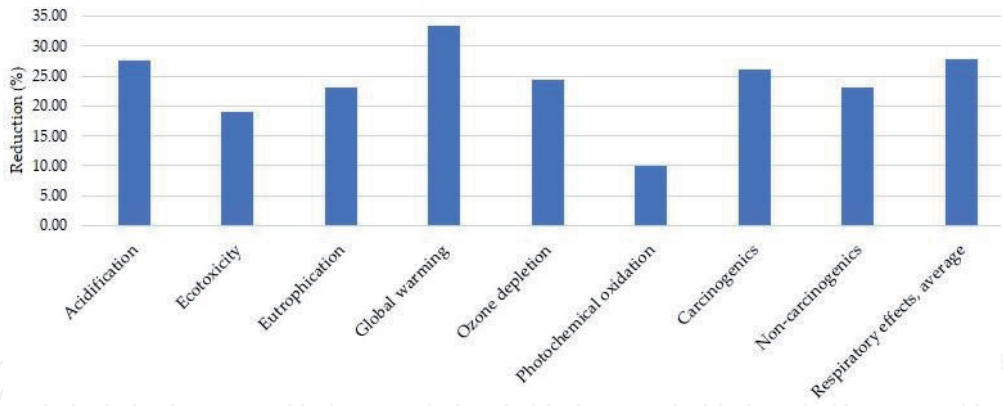

Figure 2.
Percentage of emission reduction with short slabs [85].

4.3 Increasing durability to reduce the concrete demand

4.3.1 Natural fibres to control concrete microcracking

In order to prevent internal corrosion of reinforced concrete, it is essential to reduce the formation and propagation of microcracking generated at early age by the concrete shrinkage phenomena [60, 63, 64]. Traditionally, little attention has been focused on microcracks due to their low immediate structural impact. However, from a sustainable development perspective, the control of microcracks is fundamental to limit the entrance of atmospheric agents that can corrode the rebars. Hence, the reduction of microcracks results in more durable concretes, which is a direct contribution to sustainability.

Microcracking concrete control is especially attractive in regions with aggressive environments for reinforcement corrosion, such as coastal areas. In this sense, due to its geography and the length of its coastline (6,435 km), Chile is a country that is particularly suitable for the application of these concretes. In fact, of the ten largest cities of the country, 6 are located in coastal areas.

The traditional process to limit the number and size of microcracks in concrete is the incorporation of industrial fibres [88–90]. However, abundant virgin raw materials are required to manufacture steel, glass, or plastic fibres. In this context, natural fibres have lower embedded energy, are cheaper, renewable, biodegradable and locally abundant [65–67]. In fact, they may be available as waste, which makes their use in concrete even more attractive.

Research developed by Soto et al. [91] and Okeola et al. [92] show that sisal fibres limit the propagation of microcracks in concrete. However, the incorporation of natural fibres can reduce the compressive strength. Indeed, the reduction is greater if the amount of fibres increases [93]. This has been observed in coconut fibre with reductions in compressive strength between 11% and 13% [94], jute fibre with reductions between 6% and 35% [95] and sisal fibre with reductions in compressive strength between 4.22% and 25.30% [92].

Considering that the mechanical properties, and in particular the compressive strength, is fundamental for the massive use of concrete, it is fundamental the evaluation of those properties if a particular type of natural fibre wants to be considered to control concrete microcracking. In particular, at the University of Concepción, a study has been developed in order to evaluate mechanical properties of concrete with *Eucalyptus Globulus* bark fibre, which is a waste product of the forestry industry widely available in Chile [29, 96].

A total of four fibre inclusion percentages were evaluated with respect to the weight of cement: 0.5%, 1.0%, 2.0%, and 5.0%. In order to study the potential influence of fibre absorption on the performance of the samples, the fibres were included in dry and saturated state.

The study considered, as well, the evaluation of the potential effects on the durability of the fibre when impregnated with a paraffin emulsion. This is because modification of the fibre surface with chemical or physical agents is a strategy to mitigate the potential degradation caused by the alkaline environment of the cementitious matrix (**Figure 3**).

The results indicated that there is no significant difference between incorporating the fibre in a dry or saturated state. Therefore, it is not essential to dry the fibre before incorporating it into the mixture. With respect to the fibres treated with paraffin emulsion there are no strength advantages related with their application.

In regard to mechanical behaviour, samples with 05% *Eucalyptus Globulus* bark fibre have a remarkably performance, although it is lower compared to samples without fibre. For instance, by incorporating 0.5% dry fibre (CD-0.5), the compressive strength after 28 days only differs by 0.98 MPa from the control sample without fibre (CC), which is very close to the standard error of 0.82 MPa. This trend does not agree with that reported by other researchers, which indicate significant reductions in the strength of concrete with natural fibres [91, 94, 95]. A similar behaviour was observed in the flexural strength, where the saturated samples (CS-0.5) showed a reduction of 0.20 MPa, being 0.22 MPa the standard error, i.e. the difference cannot be considered significant. Furthermore, the samples with dry fibres (CD-0.5) show a reduction of 0.7 MPa (**Figure 4**).

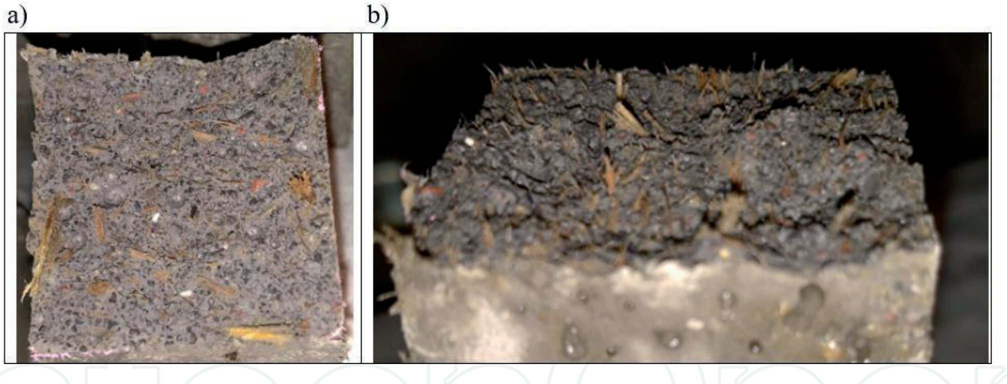

Figure 3.
Samples with E. globulus *bark fibres: (a) top view; (b) side view [29].*

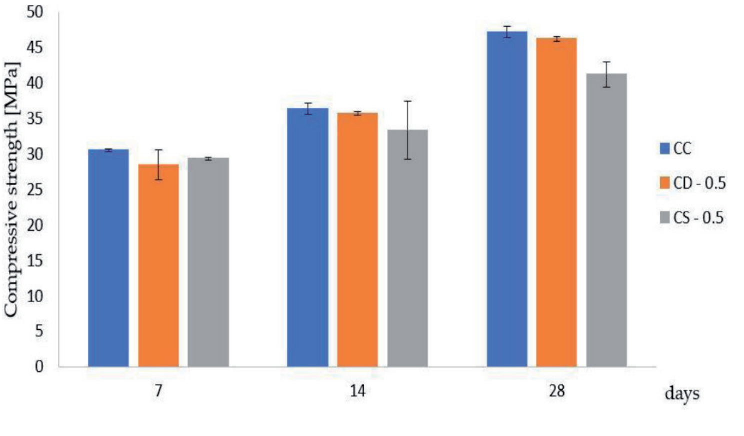

Figure 4.
Compressive strength results of concrete samples [29].

Although the limitation of microcracking in concretes was not specifically investigated, the addition of fibres is an accepted technique to control micro-cracking [88–90]. Moreover, Soto et al. [91] and Okeola et al. [92] demonstrated this using natural fibres. In particular, Araya-Letelier et al. [97] demonstrated the possibility of limiting the number and size of concrete microcracks using Chilean cements and natural fibre with 54% lower tensile strength than *Eucalyptus Globulus* bark fibres.

4.3.2 Incorporation of end-of-life tyre rubber into concrete

End-of-life tyres (ELT) represents a social and environmental problem due to the large accumulation in landfills. In fact, more than 1000 million tonnes of ELT are generated annually and more than 50% of that amount is destined to landfill or left as untreated garbage [98]. Moreover, this material produces concentrations of rats, larvae, mice and insects, increases the risk of fires difficult to extinguish [99]. This condition is aggravated by its lack of reutilisation. For instance, in Chile more than 140,000 tonnes of ELT were produced in 2019 and only 17% was recycled [100].

An attractive use of this waste is its incorporation in concrete mixes. Indeed, concrete with rubber improves properties such as energy absorption, due to its increased plasticity and ductility [101], which improves its impact behaviour and durability. However, the addition of rubber reduces the mechanical strength of the concrete [102, 103]. Therefore, to mitigate this effect, it is necessary to treat the rubber prior to its incorporation [104–106]. For instance, García et al. [107] evaluated the effects of three different treatments applied to ELT rubber before its incorporation in cement mortar samples. The treatments were hydration, oxidation-sulphonation and contact with hydrogen peroxide. The results indicate that it is possible to replace up to 5% of the fine aggregate weight with ELT rubber. Furthermore, the incorporation of hydrated ELT rubber proved to be the best treatment option from a technical, practical and economical point of view.

As the purpose is to produce a useful improvement in concrete properties and utilise waste efficiently, it is important to consider the geo-dependence of the concrete material [29]. This is particularly evident in samples made with cement containing local fly ash (Great Concepción, Chile). Indeed, this cement has a similar market cost to others national cements. However, the samples with ELT and fly ash cement are able to provide mortars that can satisfy the design requirements. Therefore, it is possible to reduce the amount of clinker while reusing a local industrial waste.

Furthermore, the adequate strength obtained in the experimental evaluation makes ELT rubber concrete an attractive alternative to improve the in-service performance of structures such as concrete crash barriers. Since rubber concrete is able to increase impact resistance and energy absorption [101], the durability of these safety elements is increased. Actually, studies indicate that concrete barriers with recycled rubber ELT have a service life 2.6 to 3.2 times longer than traditional barriers [108].

Due to the extensive road networks of the countries the benefits of this type of barrier represent not only a massive use of an industrial waste, but also bring economic, safety, and environmental benefits to the country or region where they can be applied. For instance, only in Chile the national road network roads exceed 85,000 kilometres [109].

Although the importance of geo-dependency, the results obtained in this research may be useful for other regions as well. For example, where it is possible to replace part of the cement with fly ash (produced or imported), or another cement substitute, producing similar results. If the substitute is a waste product such as fly ash, the contribution is not only technical and economic, but also it is a contribution to a sustainable development.

4.3.3 Biological self-healing concrete

A promising approach to mitigate durability problems and control microcracking of concrete is to incorporate biological elements that self-heal the material. This technique was originally developed by Dr. H. Jonkers at Delft University of Technology, who incorporate into the concrete a bacterium that has the ability to segregate calcium carbonate, sealing concrete microcracks [110]. This can represent an increment of 20% in the lifetime of a concrete structure [111]. If the same structure but with traditional concrete will need rehabilitation, and then more concrete, during its life to endure the same period of time than the self-healing concrete. Therefore, the amount of CO2 emitted into the environment decreases compared to structures built with conventional concrete. Indeed, Van Belleghem et al. [112] report that the lifetime of structures with self-repairing concrete can reduce the environmental impact by 56–75%.

Due to the biological nature of this technology and its interaction with the components of the concrete mix and the local environmental conditions, geodependence is relevant to the performance of the self-repair process. Indeed, if the ideal conditions of moisture, salinity and temperatures are not present, then the bacteria will not have sufficient stimulus to secrete calcium carbonate and the crack sealing will not be produced [113]. Similarly, cements with a higher amount of pozzolan decrease calcium carbonate precipitation which reduce the self-healing capacity of concrete [114].

In collaboration with Dr. Jonkers, bacterial growth, spore formation and production of concrete samples were developed with two types of Porland pozzolanic cements commonly used in Chile [115]. The *Bacillus pseudofirmus* bacteria solution was impregnated into expanded clays and incorporated into the concrete as a partial replacement of fine aggregate. These specimens were subjected to three different environments simulated in the laboratory: fresh water, salt water and 90% relative humidity, all at 20°C. The results at 28 days show some areas where the self-healing was 100%. Although in other cases the recovery was lower, about 90% of the specimens showed traces of calcium carbonate as a sign of the activation of the self-healing process (**Figure 5**).

The results confirm that biological self-healing of concrete can be produced with Chilean materials and regional environments simulated in the laboratory. In particular, the aggregates and cements used in the research were different from those used in the investigations of Jonkers [23, 116, 117].

Figure 5.
Concrete sample with self-healing process activated [115].

4.4 Incorporating waste into the concrete as a mean of reducing the demand for natural aggregates

4.4.1 Cooper slag as a partial replacement of concrete fine aggregates

Copper slag (CS) is a vitreous substance generated in the copper smelting process. Globally, the copper industry produces approximately 24.6 million tonnes of slag [118]. In this regard, Chile is the world's largest copper producer [119, 120], generating 2.2 tonnes of CS for one tonne of copper produced. This creates significant accumulations of slag, negatively impacting the environment.

Considering the mechanical and chemical characteristics of CS, their use in concrete mixes as a partial replacement of aggregates has been evaluated. In fact, studies indicate that replacing up to 40% of fine aggregate in concrete samples results in higher or equivalent strengths compared to samples without slag [121–123]. Similar results were reported by Al-Jabri et al. [124] and Borkowsky [125] on mortar samples with 40% and 50% fine aggregate replacement, respectively. This percentage of replacement were experimentally verified by Pérez [126] for Chilean cement and aggregates. In addition, and in order to quantify the environmental benefits of this technique, a sustainability assessment based on the five-step method of Ashby et al. [30] was performed by Pérez [126] as well. The assessment estimates the percentage of CS that could be recycled, and then, the reduction of sand demand of cement mortars and concrete. Different scenarios were considered in the analysis that the copper smelters and the aggregate extraction plants are at similar distances from the concrete plants.

The results of the sustainability analysis indicate that in the most optimistic scenario, it is possible to reuse between 58% and 64% of the CS volume produced annually. This represents an annual saving of approximately 0.7 million tonnes of sand and an annual energy saving of 210409 GJ,1737905 kg CO2 eq, 11.89 kg Sb eq, 23549348 MJ ADP, 0.08 kg CDC-11 eq, 704.14 kg C2H4 eq, 12016 kg SO2 eq and 1563 kg PO4–3 eq. For instance, shows the benefits achieved for one of the cases evaluated (**Figure 6**).

These results are relevant since, in Chile, approximately 60% of building surfaces are made of concrete and 12% of masonry [127]. Therefore, there is a great opportunity to reuse this industrial waste.

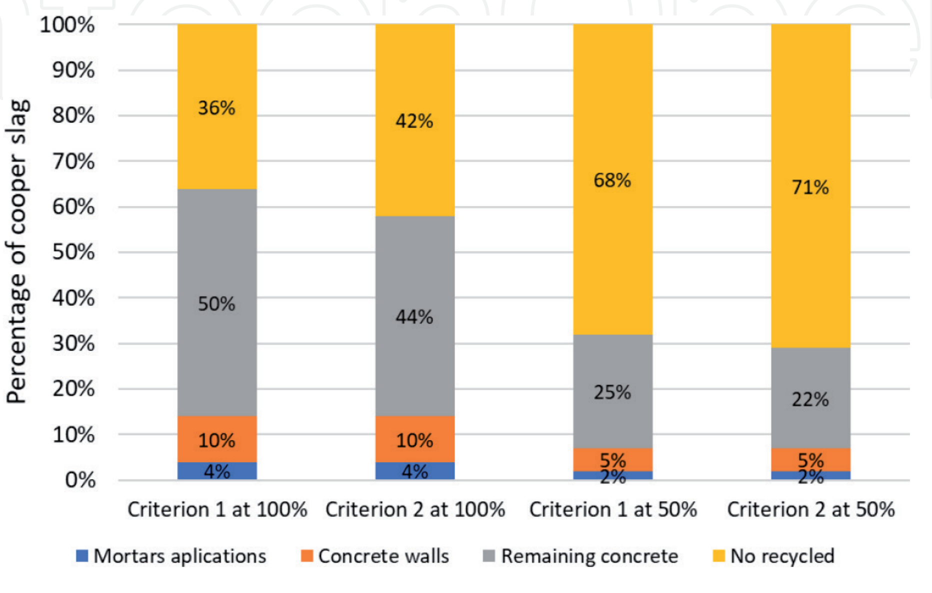

Figure 6.
Percentage of recycled CS [126].

Currently, the investigation continues at the concrete laboratory of Universidad de Concepción, with promising results in replacing more than 50% of the of the fine aggregate with CS.

4.4.2 Recycled plastics as a partial replacement of concrete fine aggregates

Various types of plastic waste have been incorporated into concrete to avoid direct contact with the environment [128–130]. In particular, in the Biobio region of Chile, the acrylonitrile butadiene styrene (ABS) is not being recycled and then its incorporation into concrete as a partial replacement of fine aggregate has been studied at the concrete laboratory of the Universidad de Concepcion (Biobio Region).

The ABS is a plastic used in the production of computer keys, appliance and power tool housings, plastic plug protectors and automotive parts such as dashboards and bumpers [131]. However, in Chile, the ABS accounts for only 2% of national plastic recycling [132], which can lead to serious waste disposal problems.

Preliminary results show that it is possible to replace up to 50% of the fine aggregate for applications as lean concrete, simple foundations, false floors and subfloors. However, optimal results were obtained when replacing 25% of the fine aggregate with ABS plastic.

Considering that concrete is a material with a high demand for natural aggregates, the strategy of using products with post-consumer recycled content, such as ABS plastic to replace sand in concrete, reduces the environmental impacts resulting from the initial stage of the concrete life cycle, extraction and processing of virgin materials.

5. Conclusions

As important as it is, sustainability related with the concrete material is more than reducing the amount of cement in the mixes. Actually, in this book chapter other approaches have been presented and analysed, starting with the phases of the concrete material life-cycle where the proposed alternatives present lower environmental impacts than the traditional ones.

Although the article mentions different examples of the approaches to develop more sustainable concrete alternatives, it goes more in details in the ones studied (or under study) at the concrete laboratory of the Universidad de Concepción. In this way, the article analyses how it is possible to reduce the demand of concrete, and therefore cement, by optimising the designs of concrete pavements. Another approach is the replacement of concrete aggregates by industrial waste such as copper slag or ABS plastic, which not only reduces the demand for the natural resource, but it contributes to solving a waste disposal problem. Finally, it is propose the incorporation, during the production stage, of natural fibres, ELT rubber or biological elements that can increase the concrete durability, which is a direct contribution to sustainability.

Hence, it is possible to develop more sustainable alternatives than the traditional ones applied in the concrete industry, which is especially relevant considering the massive use of the concrete material. However, for the development of viable alternatives, it is necessary to consider the geo-dependence of concrete. Indeed, the physical and chemical properties of the concrete components, together with the site conditions, can influence the concrete performance.

Acknowledgements

The authors express their gratitude to Dr. H.M. (Henk) Jonkers, Dr. F. (Francesco) Di Maio, Prof.dr.ir. M.J.G. (Sandra) Erkens, Dr. G. (Guang) Ye and PhD candidate Shizhe Zhang for the support received during the work developed in collaboration with Delf University of Technology. Additionally, special thanks are giving to the projects ANID PIA/Apoyo CCTE AFB170007 and VRID Multidisciplinario 219.091.051-M for funding received.

Conflict of interest

The authors declare no conflict of interest.

Author details

Mauricio Pradena* and Andrés César
Facultad de Ingeniería, Departamento de Ingeniería Civil, Universidad de Concepción, Concepción, Chile

*Address all correspondence to: mpradena@udec.cl

References

[1] Mehta PK, Monteiro PJM. Concrete: microstructure, properties, and materials. McGraw-Hill Education. 2014.

[2] Flatt RJ, Roussel N, Cheeseman CR. Concrete: An eco material that needs to be improved. J Eur Ceram Soc. 2012; 32(11): 2787-2798. https://doi.org/10.1016/j.jeurceramsoc.2011.11.012

[3] Marinković S, Malešev M, Ignjatović I. Life cycle assessment (LCA) of concrete made using recycled concrete or natural aggregates. In Eco-Efficient Construction and Building Materials. Cambridge: Woodhead Publishing; 2014. p. 239-266.

[4] Kline J, Barcelo L. Cement and CO2, a victim of success! In: Proceedings of the IEEE-IAS/PCA 54th Cement Industry Technical Conference; 14-17 May 2012; San Antonio. TX. USA. 2012. p. 1-14.

[5] Monteiro PJM, Miller SA., Horvath A. Towards sustainable concrete. Nat. Mater. 2017;16:698-699.

[6] Mindess S. Sustainability of concrete. Developments in the Formulation and Reinforcement of Concrete. 2nd ed. Vancuver: Woodhead Publishing; 2019. p. 3-17.

[7] Fernandez A, Leung Y. Technology Roadmap-Low-Carbon Transition in the Cement Industry. 2018. Available from: https://webstore.iea.org/technolo gyroadmap-low-carbontransition-in-the-cement-industry

[8] Lepech MD, Keoleian GA, Li VC, Qian S. Design of green engineered cementitious composites for pavement overlay applications. In: Proceedings of the 1st International Symposium on Life Cycle Civil Engineering; 10-14 June 2008; Varenna: Italy. 2008. P. 837-842.

[9] Potgieter JH. An Overview of Cement production: How "green" and sustainable is the industry? Environ. Manag. Sustain. Dev. 2012;1, 14.

[10] Uribe P. Explotación y venta de áridos en la comuna de Puerto Montt [thesis]. Valdivia: Universidad Austral de Chile; 2011. (In Spanish)

[11] García C, Pérez P. Alteraciones geomorfológicas recientes en los sistemas fluviales mediterráneos de la Península Ibérica. Síntomas y problemas de incisión en los cauces. Revista de geografía Norte Grande.2014;59;25-44. (In Spanish) http://dx.doi.org/10.4067/S0718-34022014000300003

[12] Opoku A, Ahmed V. Embracing sustainability practices in UK construction organizations. Built Environ. Proj. Asset Manag. 2014;4: 90-107. DOI:10.1108/bepam-02-2013-0001.

[13] World Commission on Environment and Development. Our Common Future: Report of the World Commission on Environment and Development. Oxford: Oxford University Press; 1987. 383p.

[14] Rosen MA. Engineering Sustainability: A Technical Approach to Sustainability. Sustainability. 2012;4: 2270-2292.

[15] Brunatti C, Fernandez L. El Pavimento de Hormigón. Un Camino Sustentable. In: Proceedings of the I Congreso Hormigón Premezclado de las Américas; 8-10 November 2010; Argentina: Mar del Plata. (In Spanish)

[16] Khatibinia M, Khosravi S. A hybrid approach based on an improved gravitational search algorithm and orthogonal crossover for optimal shape design of concrete gravity dams. Appl Soft Comput. 2014;16:223-233. doi:10.1016/j.asoc.2013.12.008.

[17] Kaveh A, Zakian P. Stability based optimum design of concrete gravity dam using CSS, CBO and ECBO algorithms. Iran Univ Sci Technol. 2015;5(4):419-431.

[18] Ferdowsi A, Hoseini SM, Farzin S, Faramarzpour M, Mousavi SF. Shape Optimization of Gravity Dams Using a Nature-Inspired Approach. Journal of Soft Computing in Civil Engineering. 2020;4(3):65-78.

[19] Meng Y, Ling TC, Mo KH. Recycling of wastes for value-added applications in concrete blocks: An overview. Resources, Conservation and Recycling. 2018;138:298-312.

[20] Prabhu GG, Hyun JH, Kim YY. Effects of foundry sand as a fine aggregate in concrete production. Construction and building materials. 2014;70:514-521.

[21] ACI. Measurement of Properties of Fiber Reinforced Concrete; ACI 544.2R-89; American Concrete Institute: Farmington Hills, MI, USA; 2009.

[22] Saravanan N, Buvaneshwari M. Experimental Investigation on Behaviour of Natural Fibre Concrete (Sisal Fibre). Cellulose. 2018; 54:66.

[23] Jonkers H, Thijssen A, Muyzer G, Copuroglu O, Schalangen E. Application of bacteria as self-healing agent for the development of sustainable concrete. Ecological Engineering. 2008;36: 230-235.

[24] Saleh H, El-Saied F, Salaheldin T, Hezo A. Macro-and nanomaterials for improvement of mechanical and physical properties of cement kiln dust-based composite materials. Journal of Cleaner Production. 2018; 204:532-541.

[25] Saleh et al. 2019 Saleh H, El-Sheikh S, Elshereafy E, Essa A. Mechanical and physical characterization of cement reinforced by iron slag and titanate nanofibers to produce advanced containment for radioactive waste. Construction and Building Materials. 2019; 200: 135-145.

[26] Ninčević K, Boumakis I, Marcon M, Wan-Wendner, R. Aggregate effect on concrete cone capacity. Engineering Structures. 2019;191:358-369.

[27] Mindess S, Young JF, Darwin D. Concrete.2nd ed. Upper Saddle River, NJ: Prentice-Hall. 2003

[28] Zayed A. Effects of portland cement particle size on heat of hydration (No. BDK84 977-13). Florida: Dept. of Transportation. Research Center; 2013.

[29] Mansilla C, Pradena M, Fuentealba C, César A. Evaluation of Mechanical Properties of Concrete Reinforced with Eucalyptus globulus Bark Fibres. Sustainabilty. 2020;12:10026.

[30] Ashby M, Coulter P, Ball, N. The CES EduPack Eco Audit Tool – A White Paper. Granta Design Ltd. 2011; 2:23.

[31] Hassan HS, Abdel-Gawwad HA, Vásquez-García SR, Israde-Alcántara I, Flores-Ramirez N, Rico JL, Mohammed MS. Cleaner production of one-part white geopolymer cement using pre-treated wood biomass ash and diatomite. Journal of Cleaner Production. 2019;209: 1420-1428.

[32] Maschio S, Tonello G, Piani L, Furlani E. Fly and bottom ashes from biomass combustion as cement replacing components in mortars production: Rheological behaviour of the pastes and materials compression strength. Chemosphere. 2011;85(4): 666-671.

[33] Rissanen J, Ohenoja K, Kinnunen P, Illikainen M. Partial replacement of portland-composite cement by fluidized bed combustion fly ash. Journal of

Materials in Civil Engineering. 2017;29(8):04017061.

[34] IS:1489(Part1), Product Manual For Portland Pozzolana Cement –Fly Ash based according to IS 1489 (Part 1): 2015, Bur. Indian Stand. Dehli. 2018.1489.

[35] Dhawan A, Gupta N, Goyal R, Saxena KK. Evaluation of mechanical properties of concrete manufactured with fly ash, bagasse ash and banana fibre. Materials Today. 2021;44:17-22.

[36] Fořt J, Šál J, Ševčík R, Doleželová M, Keppert M, Jerman M, Černý R. Biomass fly ash as an alternative to coal fly ash in blended cements: Functional aspects. Construction and Building Materials. 2021;271: 121544.

[37] Kupwade-Patil K, Palkovic SD, Bumajdad A, Soriano C, Büyüköztürk O. Use of silica fume and natural volcanic ash as a replacement to Portland cement: Micro and pore structural investigation using NMR, XRD, FTIR and X-ray microtomography. Construction and Building Materials. 2018;158:574-590.

[38] Jagan S, Neelakantan TR. Effect of silica fume on the hardened and durability properties of concrete. International Review of Applied Sciences and Engineering. 2021; 12(1):44-49.

[39] Sun J, Wang Z, Chen Z. Hydration mechanism of composite binders containing blast furnace ferronickel slag at different curing temperatures. Journal of Thermal Analysis and Calorimetry. 2018; 131(3): 2291-2301.

[40] Abdel Gawwad HA, Abd El-Aleem S, Faried AS. Influence of nano-silica and-metakaolin on the hydration characteristics and microstructure of air-cooled slag-blended cement mortar. Geosystem Engineering. 2017;20(5):276-285.

[41] Mo KH, Mohd Anor FA, Alengaram UJ, Jumaat MZ, Rao KJ. Properties of metakaolin-blended oil palm shell lightweight concrete. European Journal of Environmental and Civil Engineering. 2018; 22(7):852-868.

[42] Pan SC, Tseng DH, Lee C. Use of sewage sludge ash as fine aggregate and pozzolan in portland cement mortar. Journal of Solid Waste Technology and Management. 2002;28(3): 121-130.

[43] Lin KL, Chang WC, Lin DF, Luo HL, Tsai MC. Effects of nano-SiO2 and different ash particle sizes on sludge ash–cement mortar. Journal of environmental management. 2008;88(4):708-714.

[44] Alex J, Dhanalakshmi J. Ambedkar B. Experimental investigation on rice husk ash as cement replacement on concrete production. Construction and Building Materials. 2016;127:353-362.

[45] Puertas F, Varga C, Palacios M, Pellerin B, Eychenne-Baron C, Babayan D, Elkhadiri I. Alkali-activation of slag cements: Activation process, microstructure and mechanical properties. In: Proceedings of 13th International Congress on the Chemistry of Cement; 3-8 July 2011; Madrid. p. 1-7.

[46] Garcia-Lodeiro I, Fernandez-Jimenez A, Palomo A. Hydration kinetics in hybrid binders: Early reaction stages. Cement and Concrete Composites. 2013;39: 82-92.

[47] Angulo-Ramírez DE, de Gutiérrez RM, Puertas F. Alkali-activated Portland blast-furnace slag cement: Mechanical properties and hydration. Construction and Building Materials. 2017;140:119-128.

[48] Wianglor K, Sinthupinyo S, Piyaworapaiboon M, Chaipanich A. Effect of alkali-activated metakaolin

cement on compressive strength of mortars. Applied Clay Science. 2017;141:272-279.

[49] Kovalchuk G, Fernandez-Jimenez A, Palomo A. Activacion alcalina de cenizas volantes. Relación entre el desarrollo mecánico resistente y la composición química de la ceniza. Materiales de Construcción. 2008; 58: 35-52.

[50] Torres-Carrasco M, Puertas F. La activación alcalina de diferentes aluminosilicatos como una alternativa al Cemento Portland: cementos activados alcalinamente o geopolímeros. Revista ingeniería de construcción. 2017;32(2): 5-12.

[51] Hardjito D, Wallah SE, Sumajouw DM, Rangan BV. On the Development of Fly Ash–Based Geopolymer Concrete. ACI Materials Journal. 2004;101(6):467-472.

[52] Tempest B, Sanusi O, Gergely J, Ogunro V, Weggel, D. Compressive Strength and Embodied Energy Optimization of Fly Ash Based Geopolymer Concrete. In: Proceedings World of Coal Ash Conference; 7-9 May 2009; Lexington, KY: p.1-17

[53] Deepika R, Suribabu CR. Optimal design of gravity dam using differential evolution algorithm. Iran Univ Sci Technol. 2015;5(3):255-266.

[54] Hashemian FK. Structural Behaviour and Optimization of Moment-Shaped Reinforced Concrete Beams. Ann Arbor: University of Manitoba (Canada); 2012.

[55] López Vidal A, Bartolomé Muñoz, C. Fachadas de hormigón arquitectónico. Industrialización, eficiencia y estética. Alzada. 2019;119:52-57.

[56] Bartolomé C, Alarcón A, Tenorio Ríos JA, Bermejo E. New materials to increase the thermal mass of existing buildings for its energy rehabilitation. 2020

[57] Whiteley DL, Goethert K, Goodwin F, Golter HP, Kennedy J, Watternburg T, Meyer Jessi, et al. Sustainability for Repairing and Maintaining Concrete and Masonry Buildings. ICRI Committee 160. Rosemont, IL, USA; 2014.

[58] Otieno M, Alexander M, Beushausen HD. Corrosion in cracked and uncracked concrete–influence of crack width, concrete quality and crack reopening. Magazine of Concrete Research. 2010;62(6): 393-404.

[59] Snoeck D. Superabsorbent polymers to seal and heal cracks in cementitious materials. RILEM Technical Letters. 2018;30: 32-38.

[60] Paul SC, van Zijl GPAG., Šavija B. Effect of Fibers on Durability of Concrete: A Practical Review. Materials. 2020;13:4562.

[61] Ann KY, Ahn JH, Ryou JS. The importance of chloride content at the concrete surface in assessing the time to corrosion of steel in concrete structures. Construction and Building Materials. 2009;23(1): 239-245.

[62] Castañeda OH, Escobedo CJM. Durabilidad e infraestructura: retos e impacto socioeconómico. Ingeniería. Investigación y Tecnología. 2006;7(1):57-70.

[63] Berrocal CG, Löfgren I, Lundgren K, Tang L. Corrosion initiation in cracked fibre reinforced concrete: influence of crack width, fibre type and loading conditions. Corrosion Science. 2015;98: 128-139.

[64] Otieno M, Beushausen H, Alexander M. Resistivity-based chloride-induced corrosion rate prediction models and hypothetical

framework for interpretation of resistivity measurements in cracked RC structures. Materials and Structures. 2016;49(6): 2349-2366.

[65] Meredith J, Ebsworth R, Coles SR, Wood BM, Kirwan K. Natural fibre composite energy absorption structures. Compos. Sci. Technol. 2012;72:211-217.

[66] Andiç-Çakir Ö, Sarikanat M, Tüfekçi HB, Demirci C, Erdogan ÜH. Physical and mechanical properties of randomly oriented coir fiber–cementitious composites. Compos. B Eng. 2014;61:49-54.

[67] Ardanuy M, Claramunt J, Toledo Filho RD. Cellulosic fiber reinforced cement-based composites: A review of recent research. Constr. Build. Mater. 2015;79:115-128.

[68] Dash MK, Patro SK, Rath AK. Sustainable use of industrial-waste as partial replacement of fine aggregate for preparation of concrete–A review. International Journal of Sustainable Built Environment. 2016;5(2):484-516.

[69] Miller SA, Horvath A, Monteiro PJ. Impacts of booming concrete production on water resources worldwide. Nature Sustainability. 2018;1(1):69-76.

[70] U.S. Department of Transportation Federal Highway Administration. Transportation Applications of Recycled Concrete Aggregate—FHWA State of the Practice National Review. Washington, DC, USA; 2004. 47p.

[71] DiarioUChile, Los Peligros de la Extracción Masiva de Áridos [Internet]. 2015. Available from: https://radio.uchile.cl/2015/02/08/los-peligros-de-la-extraccion-masiva-de-aridos/ [Accessed: 2021-06-14]

[72] Rajan MS. Study on strength properties of concrete by partially replacement of sand by steel slag. International Journal of Engineering, Science and Technology. 2014;1(6): 96-99.

[73] Leema A, Suganya P. Performance of copper slag on strength and durability properties as partial replacement of fine aggregate in concrete. IJETAE. 2015;5(1):434-437.

[74] Thorneycroft J, Orr J, Savoikar P, Ball RJ. Performance of structural concrete with recycled plastic waste as a partial replacement for sand. Construction and Building Materials. 2018;161:63-69.

[75] Plati C. Sustainability factors in pavement materials, design, and preservation strategies: A literature review. Constr. Build. Mater. 2019;211: 539-555.

[76] Van Dam T, Taylor P, Fick G, Gress D, VanGeem M, Lorenz E. Sustainable Concrete Pavements: A Manual of Practice. Ames: National Concrete Pavement Technology Center, Iowa State University; 2012.

[77] Covarrubias TJP, Covarrubias JP. TCP design for thin concrete pavements. In: Proceedings of the 9th International Conference on Concrete Pavements; 17-21 August 2008; San Francisco, CA, USA p. 905-917.

[78] Covarrubias JP. Design of concrete pavement with optimized slab geometry. Rev. Ing. Constr. 2012; 27: 181-197.

[79] Mohod MV, Kadam KN. A comparative study on rigid and flexible pavement: A review. IOSR JMCE. 2016;13:84-88.

[80] Skrzypczak I, Radwański W, Pytlowany T. Durability vs technical—The usage properties of road pavements. E3S Web Conf. 2018;45:00082.

[81] Chávez O. Losas Cortas: Una experiencia en Nicaragua. In: Proceedings

of the VII Congreso Nacional de Ingeniería Civil; 17-18 October 2013; Managua, Nicaragua. p. 17-18

[82] Salsilli R, Wahr C, Delgadillo R, Huerta J, Sepúlveda P. Field performance of concrete pavements with short slabs and design procedure calibrated for Chilean conditions. Int. J. Pavement Eng. 2014;16:363-379. DOI:10.1080/10298436.2014.943129.

[83] Pradena M, Houben L. Load Transfer-Crack Width Relation of Non-Dowelled Jointed Plain Concrete Short Slabs. Balt. J. Road Bridge Eng. 2018;13:40-45. DOI:10.3846/bjrbe.2018.388.

[84] Roesler JR, Cervantes VG, Amirkhanian A. Accelerated performance testing of concrete pavement with short slabs. Int. J. Pavement Eng. 2012;13:494-507.

[85] César A, Pradena M. Sustainable Engineering: Load Transfer Characterization for the Structural Design of Thinner Concrete Pavements. Sustainability. 2020;12(21):9153.

[86] ISO. ISO 14040: Environmental management—Life cycle assessment—Principles and Framework; ISO: Geneva, Switzerland, 2006.

[87] ISO. ISO 14044: Environmental management—Life cycle assessment—Requirements and Guidelines; ISO: Geneva, Switzerland, 2006.

[88] Mihashi H, Ahmed SFU, Kobayakawa A. Corrosion of reinforcing steel in fiber reinforced cementitious composites. Journal of Advanced Concrete Technology. 2011;9(2):159-167.

[89] Luković M, Hordijk DA, Huang Z, Schlangen E. Strain hardening cementitious composite (SHCC) for crack width control in reinforced concrete beams. Heron. 2019; 64(1/2):181.

[90] Bertelsen IMG, Ottosen LM, Fischer G. (2020): Influence of fibre characteristics on plastic shrinkage cracking in cement-based materials: A review. Construction and Building Materials. 2020;230:116769.

[91] Soto II, Ramalho MA, Izquierdo OS. Post-cracking behavior of blocks, prisms, and small concrete walls reinforced with plant fiber. Revista IBRACON de Estruturas e Materiais. 2013;(6):598-612.

[92] Okeola AA, Abuodha SO, Mwero J. The effect of specimen shape on the mechanical properties of sisal fiber-reinforced Concrete. Open Civil Engineering Journal. 2018;12: 368-382.

[93] Pehanich J, Blankenhorn P, Silsbee M. Wood fibre surface treatment level effects on selected mechanical properties of wood fibre-cement composites. Cement and Concrete Research. 2004;34:59-65.

[94] Yalley PP, Kwan ASK. Use of coconut fibre as an enhancement of concrete. Journal of Engineering Technology. 2009;3:54-73.

[95] Zakaria M, Ahmed M, Hoque MM, Islam S. Scope of using jute fiber for the reinforcement of concrete material. Textiles and Clothing Sustainability. 2017;2(1):1-10.

[96] Bown HE, Lasserre JP. An air-drying model for piled logs of Eucalyptus globulus and Eucalyptus Nitens in Chile. N. Z. J. Forestry Sci. 2015;45(1):1-9.

[97] Araya-Letelier G, Antico FC, Carrasco M, Rojas P, García-Herrera CM. Effectiveness of new natural fibers on damage-mechanical performance of mortar. Construction and Building Materials. 2017;152: 672-682.

[98] Thai QB, Le DK, Do NH, Le PK, Phan-Thien N, Wee CY, Duong HM.

Advanced aerogels from waste tire fibers for oil spill-cleaning applications. J. Environ. Chem. Eng. 2020;8:104016.

[99] Kashani A, Ngo TD, Hemachandra P, Hajimohammadi A. Effects of surface treatments of recycled tyre crumb on cement-rubber bonding in concrete composite foam. Constr. Build. Mater. 2018;171:467-473.

[100] Gobierno Regional de Arica y Parinacota. [Internet]. 2018. Available from: https://www.goreayp.cl/index.php/noticias/1962-nueva-ley-paracombatir-140-mil-toneladas-de-neumaticos-en-desuso (Accessed: 20020-12-1).

[101] Atahan AO, Yücel AÖ. Crumb rubber in concrete: static and dynamic evaluation. Construction and Building Materials. 2012;36:617-622.

[102] Youssf O, Mills JE, Benn T, Zhuge Y, Ma X, Roychand R, Gravina R. Development of Crumb Rubber Concrete for Practical Application in the Residential Construction Sector–Design and Processing. Constr. Build. Mater. 2020;260:119813.

[103] Rashid K, Yazdanbakhsh A, Rehman MU. Sustainable selection of the concrete incorporating recycled tire aggregate to be used as medium to low strength material. J. Clean. Prod. 2019;224:396-410.

[104] Shatanawi KM, Biro S, Naser M, Amirkhanian SN. Improving the rheological properties of crumb rubber modified binder using hydrogen peroxide. Road Mater. Pavement Des. 2013;14:723-734.

[105] Mohammadi I, Khabbaz H, Vessalas K. In-depth assessment of Crumb Rubber Concrete (CRC) prepared by water-soaking treatment method for rigid pavements. Constr. Build. Mater. 2014;71: 456-471.

[106] He L, Ma Y, Liu Q, Mu Y. Surface modification of crumb rubber and its influence on the mechanical properties of rubbercement concrete. Constr. Build. Mater. 2016;120:403-407.

[107] García E, Villa B, Pradena M, Urbano B, Campos-Requena VH, Medina C, et al. Experimental Evaluation of Cement Mortars with End-of-Life Tyres Exposed to Different Surface Treatments. Crystals. 2021;11(5):552.

[108] Raj A, Arshad PU, Nagarajan P, Shashikala AP. Experimental investigation on the fracture behaviour of polypropylene fibre-reinforced rubcrete. In Structural Integrity Assessment. 2020 (pp. 335-345). Springer, Singapore.

[109] MOP. Red Vial Nacional Dimensionamiento y características. Chile: Dirección de Vialidad. Ministerio de Obras Públicas. 2020. Available from: http://www.vialidad.cl/areasdevialidad/gestionvial/Documents/RedVial Nacional2019.pdf

[110] Jonkers H. (2007) Self healing concrete: A biological Approach. Self healing materials. Springer, Dordrecht. 2007;195-204.

[111] Jonkers, H. New Materials: Biulding with Living Materials - Henk Jonkers, researcher at TU Delft [Web streaming video]. France: Hello Tomorrow; 2017 [cite 2021 May 21]. Available from: https://www.youtube.com/watch?v=xi6RJ4DpbVY

[112] Van Belleghem B, Van den Heede P, Van Tittelboom K, De Belie N. Quantification of the service life externsion and environmental benefit of chloride exposed self-healing concrete. Materials. 2017;10(1): 5

[113] Parraguez A. Estudio sobre el rendimiento de bacterias como agente de auto-reparación en el hormigón bajo

diferentes condiciones de temperatura y tipo de cemento [thesis]. Valparaíso: Universidad Técnica Federico Santa María; 2018.

[114] Becker, E. Cemento Portland– Características y Recomendaciones de Uso. Publicación de Loma Negra CIASA. 2000.

[115] Ramírez F. Evaluación de la autocuración biológica de microgrietas en hormigones bajo condiciones simuladas de laboratorio [thesis]. Concepción: Universidad de Concepción; 2020.

[116] Wiktor V, Jonkers H. Quantification of crack-healing in novel bacteria-based self-healing concrete. Cement & concrete composites. 2011;33:763-770.

[117] Jonkers H. Bacteria-based self-healing concrete. Heron. 2011;56(1/2):1-12.

[118] Gorai B, Jana RK. Characteristics and utilization of copper slag – a review. Conservation and Recycling. 2003; 39(4):299-313.

[119] Comisión Chilena del Cobre. Sección Estadísticas. Producción de cobre de mina mundial y Chile. COCHILCO, Ministerio de Minería. Chile; 2018.

[120] Minería Chilena. Participación de Chile en el mercado mundial de cobre cayó a 28% en 2019 y los rivales recortan terreno [Internet].2020. Available from: https://www.mch.cl/2020/03/16/participacion-de-chile-en-el-mercado-mundial-del-cobre-cayo-a-28-en-2019-y-los-rivales-recortan-terreno/# [Accessed: 2021-6-15]

[121] Cendoya, P. Efecto en la resistencia de las escorias de fundición de cobre como agregad fino en el comportamiento resistente del hormigón. Ingeniare. Revista chilena de ingeniería. 2009;17(1):85-94.

[122] Brindha D, Nagan S. Utilization of copper slag as a partial replacement of fine aggregate in concrete. International Journal of Earth Sciences and Engineering. 2010;3(4):579-585.

[123] Thomas J, Thaickavil N, Abraham MP. Copper or ferrous slag as substitutes for fine aggregates in concrete. Advances in Concrete Construction. 2018;6:545-560.

[124] Al-Jabri KS, Al-Saidy H, Taha R. Effect of copper slag as a fine aggregate on the properties of cement mortars and concrete. Construction Building Materials. 2011;25:933-938.

[125] Borkowsky, A. Estudio de la falla de corte de morteros de pega con escorias de fundición de cobre [thesis]. Concepción: Universidad de Concepción; 2018.

[126] Pérez M. Análisis de la utilización de escoria de fundición de cobre como alternativa sustentable de reemplazo parcial de árido fino en hormigones [thesis]. Concepción: Universidad de Concepción; 2021.

[127] Instituto del Cemento y del Hormigón de Chile. Material muros, superficie total y participación. [Internet]. 2019 https://ich.cl/estadisticas/material-muros-superficie-total-y-participacion/ [Accessed: 2020-9-23]

[128] Marzouk OY, Dheilly RM, Queneudec M. Valorisation of post-consumer plastic waste in cementitious concrete composites. Waste Manage. 2007;27(2):310-318.

[129] Choi YW, Moon DJ, Kim YJ, Lachemi M. Characteristics of mortar and concrete containing fine aggregate manufactured from recycled waste polyethylene terephthalate bottles. Constr Build Mater 2009;23: 2829-2835.

[130] Akçaözoğlu S, Atiş CD, Akçaözoğlu K. An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete. Waste management. 2010;30(2):285-290.

[131] Pérez Fernández A. Estudio de la cinética de degradación térmica de un acrilonitrilo butadieno estireno (ABS) reciclado mediante termogravimetría [thesis]. Valencia: Universitat Politécnica de Valencia; 2020.

[132] ASIPLA. Estudio sobre el Reciclaje de Plásticos en Chile [Internet]. 2019. Available from: http://www.asipla.cl/wp-content/uploads/2019/04/190328-Estudio-sobre-Reciclaje-de-Pl%C3%A1sticos-en-Chile-Resumen-Ejecutivo.pdf [Accessed: 2021-4-15]