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Sustainable Alternative of Structural Concrete Retaining Tanks

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The environmental footprint of the construction industry requires the quantification of new developments, to appraise their sustainable contribution. Recent developments in relation to merge Steel Fibre Reinforced Concrete and Self-Compacting Concrete, reveal a promising concrete technology, that requires extensive experimental studies to assess its benefits. In this study, a constructive analysis of a Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) retaining tank segment mock-up for waste-water treatment systems in terms of its sustainability and economic parameters is performed. The Integrated Value Model for Sustainable Assessment (MIVES) Multiple-Criteria Decision Making method is applied as an environmental assessment tool, which includes economic and social requirements. Although the presented methodology penalises the SFRSCC due to its high cement consumption, in aggressive exposures Reinforced Concrete (RC) also requires a noticeable cement dosage. Cement optimisation is the governing criterion and where SFRSCC has more room for improvement. However, SFRSCC favours other social issues that allow to improve its final Environmental Sensitivity Index (ESI), being superior than the RC. Overall cost would remain similar since the reduction of construction period would contribute to balance the increase of materials cost and would provide intangible benefits, such as the reduction of occupational accidents.

1. Introduction

The environmental, economic and social impact of the construction industry is a stark reality. However, awareness of these problems alone in no way implies that active measures will be taken to correct them. There is a definitive need for practical tools so that professionals may tackle these challenges. This study is part of a wider research program, merging two promising concrete technologies, namely Steel Fibre Reinforced Concrete (SFRC) and Self-Compacting Concrete (SCC). SFRC comprises those concretes in which their reinforcement is provided by short, discrete and randomly distributed fibres instead of traditional corrugated rebars. On the other hand, SCC is a liquid concrete that fills the formwork and compacts under its own weight, with no need for further consumption of energy due to vibration (Okamura and Ouchi, 2003). The interest for these two promising concrete technologies has recently increased substantially, seeking simple, practical and reliable prediction tools (Orbe et al., 2014a), a design basis and quality control methods (Faifer et al., 2011). The enhanced performance of SFRC and SCC concretes in terms of strength (Ferrara et al., 2011), durability (Figueiras et al., 2009) and sustainable benefits (Martin, 2004) have been widely discussed.

The present study first presents a literature survey on several available environmental assessment tools and previous research regarding sustainable construction materials. Next, a practical and straightforward methodology is proposed which allows designers to assess the Environmental Sensitivity Index (ESI) of different concrete structures. This procedure is based on the MIVES method, Integrated Value Model for Sustainable Assessment, which applies a Multiple-Criteria Decision Making (MCDM) technique. Following, the methodology is tested in a case study that involves the analysis of two alternatives to design a cylindrical retaining tank for a waste-water treatment system. Both are concrete structures cast on-site, whose main structural material is the same, concrete, but with different reinforcement and fresh state properties. While on the one hand a vibrated and traditionally Reinforced Concrete (RC) is considered, on the other hand a Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) is evaluated. The aim of the present paper is to demonstrate the suitability of the proposed methodology and confirm the sustainable and economic advantages of SFRSCC in comparison with the RC, particularly in aggressive exposure environments.

2. Literature survey

Over past decades, several environmental assessment tools have met with varying levels of international acceptance (Ding, 2008). A comprehensive and thorough analysis of the most representative assessment tools is summarised in Haapio and Viitaniemi (2008) and Pons and Aguado (2012). Environmental impact assessment tools, such as BREEAM and LEED, are usually applied to buildings (Lee and Burnett, 2008), rather than to civil works. Although they consider the main sustainability requirements, they are not focused on evaluating specific load bearing structural elements (Pons and de la Fuente, 2013). They also present different requirements (environmental, economic and social), rating tools, complexity and phases of building life cycle. The wide spectrum of type of structures and environmental issues, do not allow to establish a direct comparison among the available methodologies (Lee and Burnett, 2008). At first these tools only considered sustainability as one aspect of the environmental impact (Todd et al., 2001) (Cuadrado et al., 2015), although a wider scope is needed. Besides, the proven fragility of the economic system and accompanying social issues have become relevant requirements with which construction companies should comply (Ali and Nsairat, 2009).

Some methodologies are intended to quantify the impacts very precisely as input flows (material consumptions) and output flows (emissions). However, this tools require expert knowledge to acquire and process the gathered data (Zabalza Bribián et al., 2009), These data may vary notably among materials suppliers and constructors, depending on the procedure to extract raw material, the applied building techniques, etc., making even more complex the work of the designer. Knowing moreover that construction industry stakeholders do not perceive any building material particularly environmentally sustainable than others (Windapo and Ogunsanmi, 2014), it is a task hard to tackle. Those tools usually focus in occupancy impacts, e.g.: indoor environmental quality, etc, rather than initial impact quantification, more appropriate for structural elements. Also, the criteria and weightings adopted in environmental assessment tools have been usually very criticised, since they are considered subjective (Molina-Moreno and Yepes, 2015). The methodology proposed fills a gap in the evaluation tools field, with a straightforward and flexible method adaptable to local optimization criteria.

The structural design concept is a complex process, in which several stakeholders struggle to assert their interests. Multiple-Criteria Decision Making (MCDM) is a valuable tool to assist professionals with contractor and material selection tasks (Hatush and Skitmore, 1998). Among the available tools, this study applies the Integrated Value Model for Sustainable Assessment (MIVES method (Aguado et al., 2012)). Value functions are added to this MCDM, with the aim of weighting the multiple indicators that are applied. The basis of establishing those indicators lies in the experience of a panel of experts in various areas of the construction industry. Such a complex issue, may be addressed assisted by the Delphi method (Sutherland, 1975) (Hallowell and Gambatese, 2010). Based on their knowledge and an Analytical Hierarchy Process (AHP) (Saaty, 1990), a requirement tree is defined, with the corresponding criteria and indicators. The number of indicators must be limited to obtain a sufficient but not overly complex level, so that professionals may be encouraged to use it (Alwaer and Clements-Croome, 2010).

The MIVES method has been successfully applied to assess the environmental contribution of timber structures (Cuadrado et al., 2015), health and safety in construction projects (Reyes et al., 2014), school buildings (Pons and Aguado, 2012), etc. They usually analyse the sustainability index of different materials, with different suppliers. The transport distance becomes a determining factor when choosing the material and therefore, its virtues are rather misrepresented. The methodology presented analyses the sustainable contribution of alternatives based on improving conventional systems or materials that builders are more familiar with, without having to change their logistics issues, such as materials suppliers, etc.

Unlike other studies (San-José and Garrucho, 2010), this paper focuses mainly on the construction material (Bribián et al., 2011) and not exclusively on the whole Life Cycle Assessment (LCA) of the structure (Ortiz et al., 2009). It therefore presents a comparison of economic and sustainable aspects between Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC) and traditional Reinforced Concrete (RC) for the construction of cylindrical retaining walls.

3. Enviromental Sensitivity Index (ESI)

The Spanish Structural Concrete (EHE, 2008) and Steel Codes (EAE, 2011), establish a methodology, based on the above-mentioned MIVES method (Aguado et al., 2012), to determine the Contribution Index of the Structure to Sustainability, (CISS). Both apply the Environmental Sensitivity Index (ESI) of the structure for this purpose. The Codes set multiple indicators that allow a comparison between different structures, for concrete on one side and steel on the other side. These indicators are designed to compare structures, but place greater emphasis on such aspects as environmental certifications that contractors and suppliers of construction materials may display or accredited membership of quality associations. Hence, sustainability indexes may be estimated for structures built by different contractors, at different geographic locations, but with the same materials, to establish those that offer the best added value. This method is simple to implement, because its aspects are easily justifiable in an objective manner. Factors relating to both the construction process and the materials are undervalued to a certain extent.

The references to Spanish codes are necessary, as these are the first codes that introduce a quantitative sustainability assessment for the structures. The weighting factors and representative functions presented in the following tables, may be valid and initially adopted worldwide. However they could be modified, if desirable, by a panel of experts according to the idiosyncrasies of each geographical area. A unified weighting index should be established for the integration of each impact (Sakai, 2013) in an internationally plausible model, but it will be difficult to establish global parameters worldwide, as occurs with the basis of structural design. In spite of that, a comprehensible and practical methodology is presented to

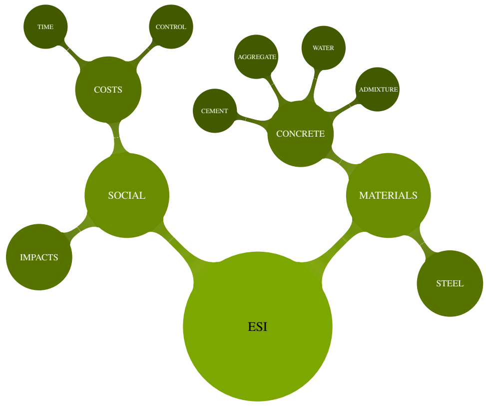

Figure 1. Relation and hierarchy of the indicators

promote the regulation of a Sustainability requirement in different countries and codes, in the same way as Serviceability and Structural Safety are nowadays. The authors also have modified the methodology presented in those codes, following the detection of some weaknesses.

As a result, 8 new indicators are defined in this section, in part by modifying those contained in the above standards and by adapting them to the case study. The relative weights of each criterion (Table 1) are defined applying the AHP methodology (Saaty, 1990), while the indicators and the trends of their value functions have been obtained through Delphi methodology (Hallowell and Gambatese, 2010). Thus, the structural and constructive solution can be directly compared, can be carried out by the same construction company, with the same material suppliers (rebar or fibres manufacturers and concrete), at the same geographic location. The hierarchical relation between those indicators is depicted in Figure 1. It shows, on the one hand, the indicators linked to the materials, which are divided into concrete and steel reinforcement, and, on the other hand, those directly related to the construction process.

These indicators analyse the consumption of the resources that may be used, in terms of economic and environmental aspects. They strengthen the estimation of cost reduction for each item that constitutes the project, using a system of weightings according to their environmental impact during manufacture and waste management. Furthermore, these criteria also consider some social aspects such as the employment conditions of workers and

Environmental requirement	Weighting coefficient α_i	β_i	γ_i
Cement optimising	0.60	0.70	0.60
Characteristics of aggregates			0.20
Water management			0.10
Characteristic of admixtures			0.10
Optimisation of reinforcement		0.30	1.00
Impact control	0.40	0.25	1.00
Construction time frame		0.75	0.40
Control of materials			0.60

Table 1. Weighting coefficients for each criterion

Environmental requirement	Weighting coefficient K_i	m_i	n_i	A_i
Cement optimising	1.21	-0.25	40	2.1
Characteristics of aggregates	1.05	-0.40	40	2.2
Water management	1.05	-0.40	40	2.2
Characteristic of admixtures	10.5	-0.10	100	2.0
Optimisation of reinforcement	1.20	-0.40	55	2.5
Impact control	10.5	-0.001	1	1.0
Construction time	1.21	-1.05	50	0.75
Control of materials	1.21	-0.40	40	1.6

Table 2. Defining parameters for each representative value function

disruption occasioned to local residents. Higher values of the resulting indicators, represent a higher environmental sensitivity.

$$ESI = \sum_{i=1}^{i=8} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i \qquad i = 1, ..., 8 \tag{1a}$$

$$CISS = a + b \cdot ESI \tag{1b}$$

Equations (1a) and (1b) show the conventional estimation of the ESI and CISS sustainability indexes in accordance with the procedure established in the Spanish concrete and steel codes. Parameters α, β and γ attach weights to the value coefficients, V_i, depending on the importance settled for each of the established 8 indicators (Ugwu et al., 2006), as shown in Table 1. The value of those influences are divided into hierarchical branches, forming each sublevel a new analysis unit. Parameters a and b, needed to estimate the CISS, represent the social contribution of the project and the extension of the structural life span. The analysis of these two parameters is beyond the scope of the paper, so the study will only focus on the estimation of the ESI.

$$V_i = K_i \left(1 - e^{m_i \left(\frac{P_i}{A_i}\right)^{n_i}}\right) \tag{2}$$

The multiple value coefficients, V_i, for each indicator can be calculated according to Equation (2). They describe the result of a logistic function, defined by the parameters K_i, m_i, A_i and n_i (Table 2), the input of which are the indicators score, P_i. Those scores can be obtained, as shown in Equation (3) for each percentage of the total mixed amount of n concrete batches, $p_{i,j}$, based on the attributes that quantify the parameter $\lambda_{i,j}$. The latter is related to the amount of used raw materials and certain actions taken to improve the temporal and economic cost of the construction process and to reduce the impacts that are caused. The parameters governing the shape of the logistic functions, may displace the inflexion point and the growth rate to arrive at a minimum indicator score that obtains an acceptable value coefficient. This behaviour depends on the interest to promote more involvement in decision making towards sustainability (Delmas and Toffel, 2004). The following sections define the representative value functions of each environmental criterion and the arguments concerning the adopted parameters are exposed.

$$P_i = \frac{1}{100} \sum_{\substack{j=1 \\ i=1}}^{\substack{i=8 \\ j=n}} p_{i,j} \cdot \lambda_{i,j} \tag{3}$$

3.1. Environmental criterion of optimisation of the cement

This indicator reflects the environmental contribution in relation to the reduction of cement dosages and the use of cement additions. This is the criterion that further influences the final environmental sensitivity (Huntzinger and Eatmon, 2009) (Damineli et al., 2010) (Phair, 2006). The smallest reduction is defined by the minimum required content specified in EHE (2008) in line with its exposure category. Reductions in the use of cement are therefore encouraged, in compliance with the requirements established in the current codes regarding the level of exposure of each structure.

The $\lambda_{1,j}$ parameter is linked to the cement dosage used according to an specific exposure category, as shown in Table 3. Those values are valid for blended cements (Flatt et al., 2012), while the use of Ordinary Portland Cement (OPC) should be penalised by an additional 80% reduction factor. The values corresponding to the intermediate quantities can be interpolated on a linear basis. In accordance with ISO 22965-1 (2007), the UNE-EN 206-1 (2008) addresses seven exposure categories, each of which has a different degree of severity, denoted by its relevant class. The categories are also divided into; on the one hand, general exposure to non-aggressive (I, equivalent to X_0 and C0 according to Model Code 2010 and ACI318, respectively), normal (II_a and II_b; XC; C/W), and marine environments (III_a to III_c; XS; C) and to chloride ions not of marine origin (IV; XD; C). On the other hand, specific exposure categories apply to concrete exposed to chemically aggressive environments (Q_a to Q_c; XA; S), freezing and thawing (H and F; XF; F) and erosion (E; XM). In consonance with UNE-EN 206-1 (2008), each class establishes different requirements for maximum water/cement ratios, minimum cement dosage and rebar coverage. The first two conditions usually lead to a higher compressive strength. Although some authors state that the minimum cement contents established in the standards are too high (Wassermann et al., 2009), in this study they have been considered fixed, setting the highest value that can be achieved. Cement content may be reduced due to the partial replacement of cement by the addition of supplementary cementitious materials: i.e. the by-products of industrial processes, such as fly ash, ground granulated blast furnace slag or silica fume (Meyer, 2009). This will encourage the use of ECO-SCC (Wallevik et al., 2009), among other new developments (Aïtcin, 2000) (Scrivener and Kirkpatrick, 2008).

3.2. Environmental criterion of optimisation of aggregates

The present indicator quantifies the environmental influence of aggregate size and origin in the concrete mix. The reduction of maximum gravel size and the increase in the use of sands or fines requires higher levels of energy consumption, which the criterion penalises.

Depending on the percentage of recycled concrete aggregates (RCA) used in the concrete mix and the nominal maximum size of the coarse aggregate, Table 4 provides the parameter $\lambda_{2,j}$ to quantify the value function of this indicator. Although the use of recycled aggregates is promoted, exceeding 20% of substitution may cause a reduction in the compressive strength of the concrete and may increase the water absorption rates of the aggregates (Etxeberria et al., 2007) (Corinaldesi and Moriconi, 2009) (Limbachiya et al., 2012) (Kou and Poon, 2009), leading to a mix-design that is not cost effective. This is the reason why a more noticeable improvement is achieved until 20% of RCA use.

3.3. Environmental criterion of optimisation of the mixing water

The third indicator rates the environmental contribution of the optimisation of mixing water consumption. As water is an increasingly scarce resource, mixes with a reduced volume of water are of evident interest. This reduction in the use of water may also result, with the appropriate admixtures, in a more compact and workable concrete that is both resistant and durable. Nevertheless this criterion, along with the admixtures, has the least impact on the overall behaviour.

When defining the values for Table 5, it has been established that $\lambda_{3,j}$ acquires a value of 75 for the amount of water that is strictly necessary, in accordance with the maximum w/c ratio and the minimum cement dosage required by the structural concrete code. From that value, any increase in water impairs the achievement of better outcomes and vice versa. At the same time, this can cause reductions in strength and can increase the permeability of the concrete. The latter aspect is closely linked to its durability and forms the basis for establishing the indices presented in this paper The reduction of water can be achieved by the use of chemical admixtures, specially VMA, taking into account their influence in the final environmental sensitivity of the project in the Subsection 3.4.

3.4. Environmental criterion of optimising the use of admixtures

This indicator shows the environmental contribution of chemical admixtures dosed in the mix-design of the concrete. Although these products can greatly improve the properties of the material in both the fresh and the hardened state, their use also presents an inherent

Exposure class		Cement dosage (kg/m^3)										
		250	275	300	325	350	375	400	425	450	475	500
Gen.	Spe.	$\lambda_{1,j}$										
I		100	90	80	70	60	50	40	30	20	10	0
II_a		—	100	90	80	70	60	50	40	30	20	10
II_b		—	—	100	90	80	70	60	50	40	30	20
III_a		—	—	100	90	80	70	60	50	40	30	20
III_b		—	—	—	100	90	80	70	60	50	40	30
III_c		—	—	—	—	100	90	80	70	60	50	40
IV		—	—	—	100	90	80	70	60	50	40	30
	Q_a	—	—	—	100	90	80	70	60	50	40	30
	Q_b	—	—	—	—	100	90	80	70	60	50	40
	Q_c	—	—	—	—	100	90	80	70	60	50	40
	H	—	—	100	90	80	70	60	50	40	30	20
	F	—	—	—	100	90	80	70	60	50	40	30
	E	—	—	100	90	98	70	60	50	40	30	20

Table 3. Optimisation of cement dosage

	Nominal maximum size of coarse aggregates (mm)							
	8	10	12	16	20	25	30	40
RCA (%)	$\lambda_{2,j}$							
0	0	10	15	20	25	30	35	40
20	45	50	55	60	65	70	75	80
100	65	70	75	80	85	90	95	100

Table 4. Optimisation of size of the aggregates

risk. However, it is very limited due to the low proportions in which it is used.

The parameters $\lambda_{4,j}$ are added for the various admixtures mixed with the concrete, shown in Table 6 as a percentage by weight of cement (% woc). These coefficients have been determined on the basis of the biodegradability of these admixtures and the environmental risks associated with their active compounds in aqueous solutions. The values corresponding to intermediate percentages by weight of cement are obtained by linear interpolation.

3.5. Environmental criterion of optimisation of the reinforcement

Reinforcement optimisation and its environmental contribution are governed by the criterion presented in this section. Its intention is to encourage designers to optimise steel usage and to simplify and to reduce the resources for on-site assembly and usage.

The parameters $\lambda_{5,j}$ shown in Table 7 are split into two columns, depending on whether the structure is cast with a conventional reinforced concrete or with the SFRSCC presented in this paper. According to this indicator, the use of large meshes is encouraged to reduce overlaps in their extensions, resulting in reduced usage of steel. More than 5 overlaps (n) yield no improvement in the value function. The common union systems for corrugated rebars are also analysed, to promote simple non-welded ties. Best practice for rebar processing is also encouraged, based on the percentage (%) of the reinforcement supplied according to appropriate standards. Fibre reinforcement requires neither assembly nor overlaps, nor reinforcement processing, so it directly takes the maximum values.

3.6. Environmental criterion of impact control

This indicator assesses the impacts of the construction process on the environment and occupational health and safety (OHS), concerning the variable to be analysed, in this case, the structural material. These impacts are quantified in terms of a reduction in the use of plastic materials, the need for further manual work after casting, whole-body vibration (WBV) (Kittusamy and Buchholz, 2004), low-back disorders (LBD) (Hess et al., 2004) or other musculoskeletal disorders and other occupational health risks such as skin and ear affections (Reyes et al., 2014). The impacts of the

Exposure class Gen.	Spe.	145	150	155	160	165	170	175	180	185	190	195
		Water amount (l/m^3) $\lambda_{3,j}$										
I		90	85	80	75	75	65	55	45	35	25	15
II_a		95	90	85	80	75	65	55	45	35	25	15
II_b		95	90	85	80	75	65	55	45	35	25	15
III_a		75	75	65	55	45	35	25	15	5	0	0
III_b		90	85	80	75	75	65	55	45	35	25	15
III_c		85	80	75	75	65	55	45	35	25	15	5
IV		90	85	80	75	75	65	55	45	35	25	15
	Q_a	90	85	80	75	75	65	55	45	35	25	15
	Q_b	100	100	95	90	85	80	75	65	55	45	35
	Q_c	85	80	75	75	65	55	45	35	25	15	5
	H	95	90	85	80	75	65	55	45	35	25	15
	F	90	85	80	75	75	65	55	45	35	25	15
	E	80	75	65	55	45	35	25	15	5	0	0

Table 5. Optimisation of mixing water

Subcriteria							
Polyfunctional	Dosage (% woc)	0	0.25	0.50	0.75	1.00	$\geq$ 1.25
	$\lambda_{4,j}$	+18	+16	+12	+8	+4	+0
Superplasticiser	Dosage (% woc)	0	0.50	1.00	1.50	2.00	$\geq$ 2.50
	$\lambda_{4,j}$	+16	+14	+10	+6	+2	+0
Retardant	Dosage (% woc)	0	0.50	1.00	1.50	2.00	$\geq$ 2.50
	$\lambda_{4,j}$	+18	+16	+12	+8	+4	+0
Accelerator	Dosage (% woc)	0	3	5	7	9	$\geq$ 12
	$\lambda_{4,j}$	+12	+8	+4	+2	+1	+0
Air entrainer	Dosage (% woc)	0	0.05	0.10	0.15	0.20	$\geq$ 0.25
	$\lambda_{4,j}$	+18	+16	+12	+8	+4	+0
Water-repellent	Dosage (% woc)	0	0.50	1.00	1.50	2.00	$\geq$ 2.50
	$\lambda_{4,j}$	+18	+16	+12	+8	+4	+0

Table 6. Optimisation of chemical admixtures

sub-criteria established in Table 8 have been weighted according to their ease of implementation and the actual trends reflecting multiple affections (Stocks et al., 2015).

3.7. Environmental criterion concerning the construction period

This criterion is intended to assess the environmental contribution provided by materials and construction systems that reduce deadlines and it therefore covers all hazards involved in the construction process.

The values of the input parameter $\lambda_{7,j}$ are shown in Table 9. Depending on the percentage of prefabrication of the structure, a higher value is adopted due to its fast assembly, ranging from 0, when the structure is cast on-site, to 100, when all the structure is formed by precast concrete. Intermediate situations may add an improved rating if system as SCC and SFRC are used, as casting and reinforcement work is notably reduced.

Subcriteria	RC $\lambda_{5,j}$	SFRSCC $\lambda_{5,j}$
Number of overlaps (n)	+35-n·7≥0	+35
System of union		
⇒ Welding	+0	+30
⇒ Mechanical tied or similar	+30	
Reinforcement processing[a] (%)	+35·%/100	+35

[a] best practices according to UNE 36831 (2006), ACI 315-99 (1999) or equivalent

Table 7. Optimisation of reinforcement

Subcriteria	$\lambda_{6,j}$
Reduction of auxiliary elements (rebar spacers, rebars caps as impalement protection, etc.)	+10
Use of systems that reduce the influence of operators to avoid subsequent repair works (blowholes, etc.)	+10
Mitigation of musculoskeletal disorders (LBD, WBV, etc.)	+30
Safety of ironworkers (reduction in hazards, falls, etc.)	+20
Improvements in health conditions (skin and ear affections, etc.)	+30

Table 8. Impact control

Use of precast systems %	Use of SFRSCC $\lambda_{7,j}$	
0	0	+20
20	20	+20
40	40	+20
60	60	+20
80	80	+20
100	100	—

Table 9. Reduction of construction times

3.8. Environmental criterion for the control of materials

The environmental criterion for material control assesses the impact of controlling materials to ensure proper performance of the structure. For example, the amount and orientation of the steel fibres within the concrete matrix can be determined by destructive or non-destructive tests, such as magnetic methods or the transmission and reception of different signals or waves. Likewise, in order to control mechanical properties such as compression and tensile strength, cubic specimens can be used to reduce sulphur used in facing operations and the volume of concrete that is required. Besides the traditional cylindrical specimen, the EHE (2008) code even allows the use of cubic specimens with 100 mm sides in concretes the compression strength of which, f_{ck}, equals or exceeds 50 MPa. This condition applies as long as the maximum size of the coarse aggregate does not exceed 12 mm, which coincides with the characteristics of the SFRSCC. The amount of fibres can be determined according to the EN 14721 (2006), where the fibres must be pulled apart from the matrix in fresh or hardened states. Alternatively, non-destructive tests can be performed (Orbe et al., 2014b) and the specimens may be reused for further analysis. Moreover, the Barcelona test (Pujadas et al., 2013) is of great interest, as it characterises the tensile strength of the SFRC with smaller specimens, a 150 mm side cube, rather than the extended bending test (EN 14651, 2007) that is often used. The use of NDT (Torrents et al., 2012) that also determines the characteristics and properties of the materials is encouraged.

The values of the $\lambda_{8,j}$ parameter are obtained from Table 10, adding the values linked to each type of test. As in the indicator of the reinforcement optimisation environmental criterion, two cases have been split, linked to the use of RC and SFRSCC, respectively. In the former, the tensile strength of the matrix is not characterised as it contains no fibres. In both cases, priority is given to the use of smaller specimens and to the determination of characteristic and mechanical properties by non-destructive means. Their use implies lower material consumption for material control and, therefore, less wastage.

4. Case study

The structural suitability of SFRSCC for designing cylindrical retaining tank elements has been demonstrated in previous research (Orbe et al., 2012). As high walls require pre-stressed concrete, due to their higher tensile stresses, the height is limited, so both materials may be compared. Finally, the dimensions and the loads of the structure are set to 10 metres in diameter, 4 metre in height and 0.25 metre in width, containing a liquid of similar density to water. The compared concrete mix-designs, summarised in Table 11, have their origin in previous research for the SFRSCC and usual RC dosages mixed in the collaborating batching plant, both for aggressive exposure classes (Subsection 3.1), IV+Q_b (Orbe et al., 2015).

Properties	Specimen/Method	RC	SFRSCC
		$\lambda_{8,j}$	
Compression strength[a]	h=300mm, ϕ=150mm	+0	+0
	a=150mm	+60	+30
	a=100mm	+100	+40
Fibre amount	Destructive testing		+0
	Non-destructive testing		+20
Tensile strength	l=600mm[b], a=150mm		+0
	a=150mm		+30
	Non-destructive testing		+40

[a] EN 12390-3 (2009) for RC and UNE 83507 (2004) for SFRC, or equivalent
[b] ASTM C1609 / C1609M-12 (2012) allows the testing of 100x100x350 mm specimens

Table 10. Performed quality control tests

Component		RC	SFRSCC
Cement	kg/m^3	350	430
Sand 0/4	kg/m^3	814	1100
Gravel 4/12	kg/m^3	298	650
Gravel 12/25	kg/m^3	764	—
Water	l/m^3	156	175
Polyfunctional	l/m^3	4.20	4.48
Superplasticiser	l/m^3	—	5.03
Fibres HE 1/50	kg/m^3	—	50
Rebar	kg/m^3	70	—

Table 11. Mix-designs

The study is focused on a mock-up of the structure. The component when cast was 3 metres in height, 6 metres in length, with a width of 0.15 metres. These dimensions are sufficiently representative of the structure under analysis and in line with the subsequent handling and cutting operations to obtain specimens with normalised dimensions for the standard strength tests. The figures in this paper indicate the data for RC by a dashed line and the one corresponding to SFRSCC, by a dotted line.

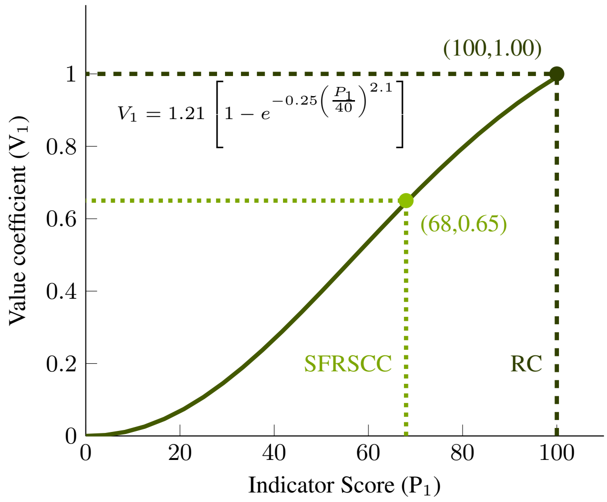

Figure 2. Value function for optimising cement

Figure 2 shows the sigmoid-shaped value function for cement optimisation, Subsection 3.1 and illustrates the growth of the environmental sensitivity of the project according to this indicator. The high cement content values are penalised with reduced or zero $\lambda_{1,j}$ values. The parameter approaches the maximum value, 100, as it approaches the minimum cement dosage required by the codes for a given exposure category. The initial growth rate is approximately exponential until a critical value is exceeded, which causes a decrease in the growth rate. The growth, although gradually reduced, never completely stops, as the reduction of cement dosage always remains environmentally interesting until the criterion reaches a saturation point. The representative value, P_1, of this indicator should reach 65, at least, to obtain a minimum value coefficient, V_1, of 0.50. As the usage of smaller amounts of cement is interesting, the inflexion point of the sigmoid function shifts to the right, resulting in a more rigorous indicator. Therefore, the assumable cement excess is bounded, depending on each exposure category, to a value of between 25% and 35% of the minimum cement dosage. According to the potential use of the structure in a waste-water treatment system, an aggressive specific exposure category, Q_c, must be established. the RC case achieves the highest value (350 kg/m^3 of cement $\rightarrow \lambda_{1,j}$=100 $\rightarrow V_1$=100), while the SFRSCC is notably disadvantaged on the basis of the cement amount described in Table 11 (430 kg/m^3 of cement $\rightarrow \lambda_{1,j}$=68 $\rightarrow V_1$=0.65).

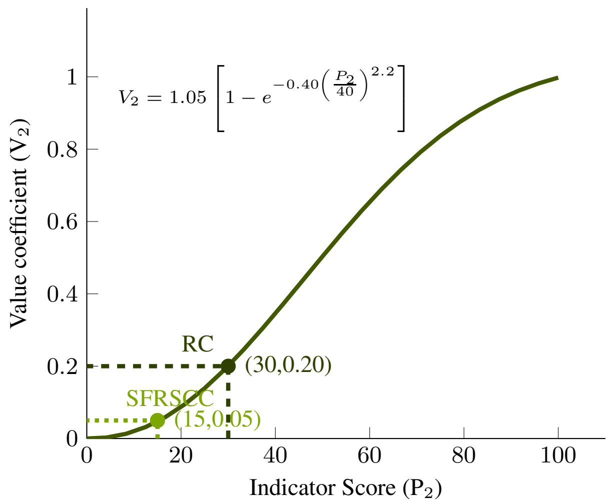

Figure 3. Value function for optimising aggregate size

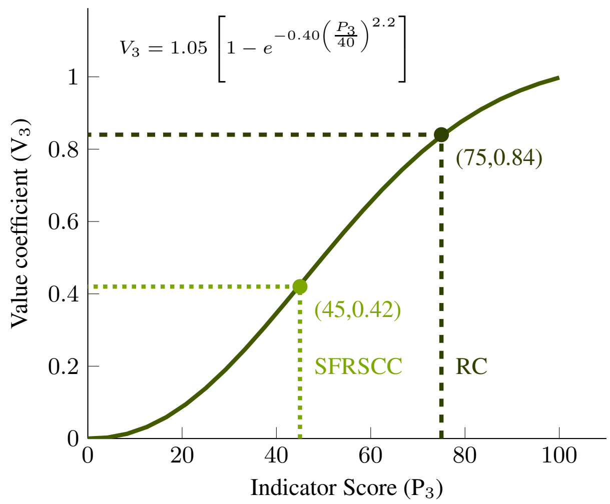

Figure 4. Value function for optimising mixing water

In the case of aggregates optimisation, Subsection 3.2, the value function also shows a non-symmetric sigmoid curve, as may be seen in Figure 3. The value function shows, as in the previous case, an initial exponential growth until the inflexion point is reached, followed by a marked reduction. Hence, the low differences between the biggest maximum sizes, even though the differences are high, if compared to smaller sizes. According to the present criterion, its environmental sensitivity is linked to the reduction of the energy consumption necessary to crush the aggregates. Thus, parameter $\lambda_{2,j}$ varies from 0 to 100, for maximum aggregate sizes ranging between 8 and 40 mm, respectively. It therefore encourages a reduction in the amount of fine aggregates coupled with a maximum aggregate size that is as coarse as possible, as is often the case in traditional concrete mixes. In this situation, the SCC requires a smaller sized aggregate and a higher proportion of fines to achieve the necessary consistency and to provide the concrete matrix with stability and workability. It is also of interest to consider the supply of raw materials from quarries with banks of limited-size gravel, which reduces crushing work. The use of RCA has not been considered in the case studies, therefore the maximum coarse aggregate size is set in 25 mm for the RC ($\lambda_{2,j}$=30 $\rightarrow$ V_2=0.20) and, markedly lower, at 12 mm for the SFRSCC ($\lambda_{2,j}$=15 $\rightarrow$ V_2=0.05).

Figure 4 illustrates the corresponding value function for the indicator that assess the water optimisation. This sigmoid function is totally symmetric, obtaining 50 as the representative value, a value coefficient equal to 0.50. The representative value functions of the case studies regarding this indicator were obtained in a similar way to the method presented in Subsection 3.1. In this case, the RC is mixed with the strict 0.45 w/c ratio (156 l/m^3 of water $\rightarrow$ $\lambda_{3,j}$=75 $\rightarrow$ V_3=0.84). Although the SFRSCC has been mixed with a lower w/c ratio, 0.40, the above mentioned higher cement amount leads also to a higher water consumption (175 l/m^3 of water $\rightarrow$ $\lambda_{3,j}$=45 $\rightarrow$ V_3=0.42).

The function shown in Figure 5 based on the chemical admixtures dosage presents a concave shape. There is no inflexion point that reflects a reduced growth rate; i.e. the lower the use, the lower the impact. Although the value coefficient can adopt values of between 0 and 100, the lower boundary is practically unattainable, as it would require excessive and inappropriate admixture usage. Obviously, there are improvements linked to the use of these components that are quantified by their respective indicators. Although its influence is not very noticeable in the final index, the case studies adopt similar values according to the % by weight of cement of the admixtures mixed with the concrete. While RC is mixed with a 1.4% by *woc* of polyfunctional admixture ($\lambda_{4,j}$=82 $\rightarrow$ V_4=0.68), the SFRSCC contains a 1.2% of polyfunctional and 1.25% of superplasticiser ($\lambda_{4,j}$=74.8 $\rightarrow$ V_4=0.57). The approximate densities of each admixture are 1.18 g/cm^3 and 1.07 g/cm^3, respectively.

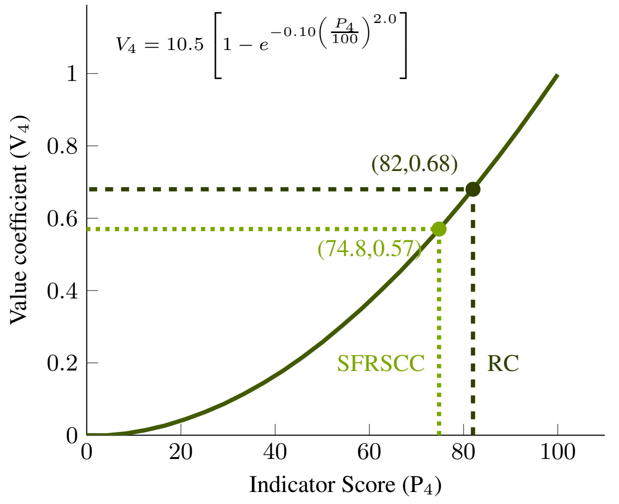

Figure 5. Value function for optimising the quantity of admixtures

According to the reinforcement optimisation criterion, Figure 6 illustrates the established value function. The sigmoid function presents an inflexion point which shifts to the right, as the very few actions for the enhancement of their environmental impact are underestimated. In the case study, the rebar reinforcement summarised in Table 11 would comprise identical meshes for the inner and outer faces of the RC segment, with ϕ12 mm rebars and a spacing of 20 cm in both directions. Despite a slight reduction due to an horizontal overlap in the RC case, both situations achieved a high representative value function, $\lambda_{5,j}$=93 $\rightarrow$ V_5=0.93 for RC and $\lambda_{5,j}$=100 $\rightarrow$ V_5=0.100 for SFRSCC

However, a lineal relation between the representative value obtained with each of them and the value coefficient has been established (see Figure 7). Any action taken in this regard will similarly protect against hazards in the construction process that threaten human life, the environment and the health and safety of workers. It is assumed that for both materials preventive measures are taken to avoid hazards and falls from height. Besides these, the use of SFRSCC will lead to reductions in some auxiliary plastic elements and mitigate the musculoskeletal and sensorial disorders, among others.

The convex shape of the representative function for the impact control indicator is shown in Figure 8. In this case, it can be observed that any minimum action established for reducing the

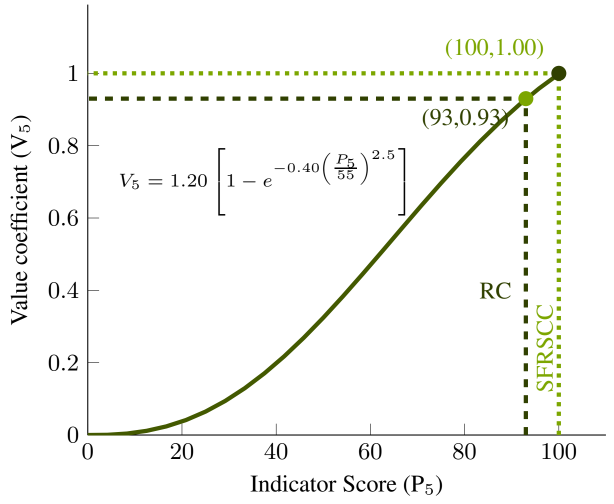

Figure 6. Value function for optimising the reinforcement

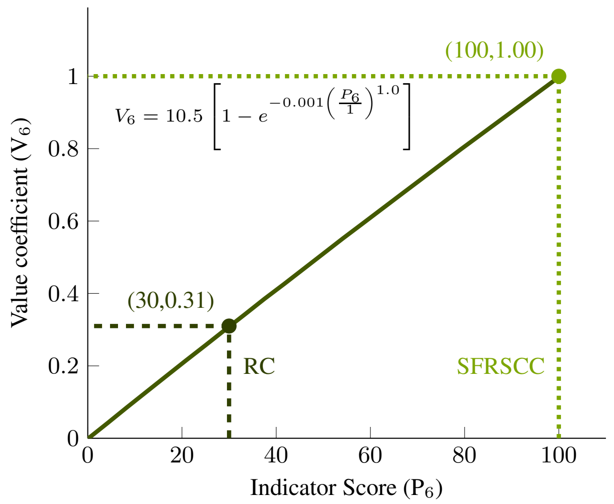

Figure 7. Value function for impact control

deadlines has a very positive impact on the final result, with a significant increase in the value coefficient. For the case studies, an on-site casting process is established without any precast element, obtaining a low value for RC ($\lambda_{7,j}$=0 $\rightarrow$ V_7=0.00). However, the SFRSCC case will adopt some positive assessment due to the time reduction achieved by the simultaneous use of SCC and SFRC ($\lambda_{7,j}$=20 $\rightarrow$ V_7=0.50)

The value function illustrated in Figure 9, corresponds to the waste optimising criterion and acquires a sigmoid shape with a similar growth rate along all its length. Since the inflexion point shifts to

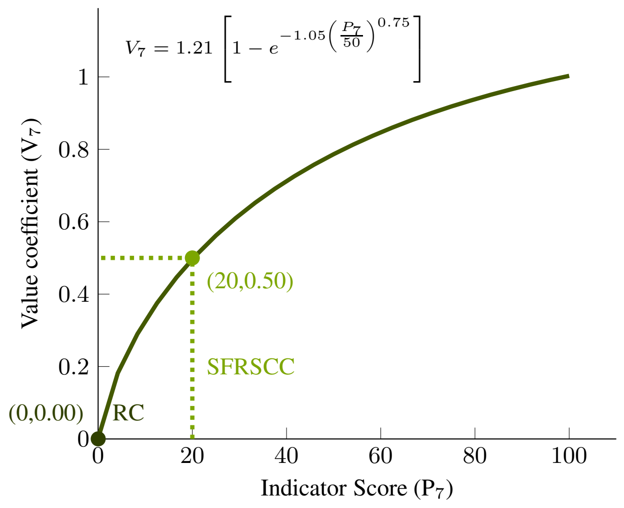

Figure 8. Value function for construction time

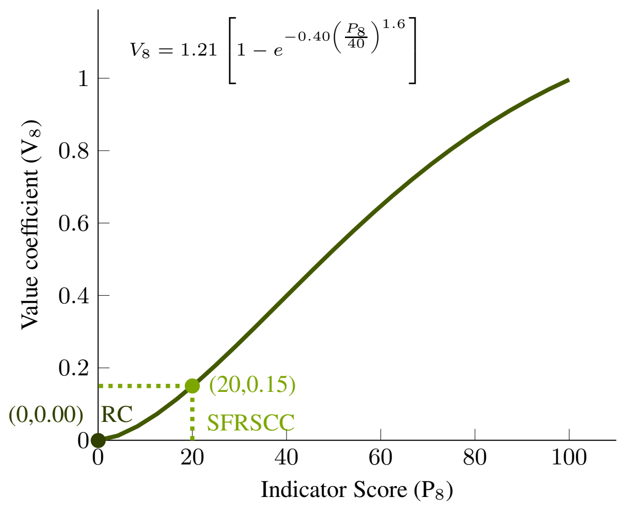

Figure 9. Value function for optimising generated waste

the left, the adoption of some actions is encouraged, without the need to meet all the requirements. In both cases, and until new testing methods are widely accepted, common size specimens are considered for testing: cylindrical ones for compressive strength (RC $\rightarrow \lambda_{8,j}$=0 $\rightarrow V_8$=0.00) and large prismatic ones for the tensile strength tests on SFRSCC. Based on the experience of the authors, it is considered reasonable to analyse the fibre content on cubic specimens, which may be obtained by trimming the large specimens after the tensile tests (SFRSCC $\rightarrow \lambda_{8,j}$=20 $\rightarrow V_8$=0.15).

5. Discussion of results

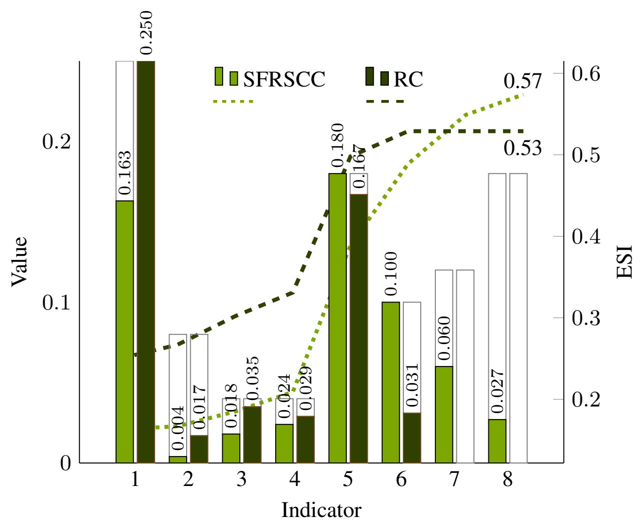

Figure 10. Comparison between both case studies

5.1. Environmental comparison

According to the methodology presented in the previous subsections, it is possible to establish the ESI values that correspond to each of the proposed design options. That will result in different CISS values for the same construction constraints. Favourable conditions that do not excessively penalise either case will be adopted for various issues that are not usually defined, thereby avoiding fictitious differences.

Figures 2 to 9 show the representative value functions and the corresponding value coefficients for each of the indicators. After applying the weighting coefficients (Table 1), Figure 10 is obtained which provides information about the value obtained for each of the eight indicators, coloured bars, and the potential maximum contribution, uncoloured bars, that can be achieved in each one. Some of the indicators, i.e.: criterion 2 for SFRSCC and criteria 7 and 8 for RC, are not shown as the value obtained is null and they therefore provide no improvements to sustainability. Besides, the dotted lines sum the values of each indicator and depict the final ESI for both cases, SFRSCC and RC. It is evident that some indicators, i.e. increased use of cement or reinforcement, are the most representative and which have the most significant environmental impact. Also, the generated waste have a paramount influence in the obtained ESI value. The overall environmental contribution of SFRSCC is similar to or even better than RC, a 7.5% higher, 0.57 and 0.53 for SFRSCC and RC respectively.

Analysing the indicators associated to materials, it can be observed that the main focus lies on cement and the aggregates, first and second indicators respectively. Water, admixture and reinforcement optimisation do not allow much room for improvement or this is not sufficiently appreciable. These are either close to saturation or present low weighting coefficients. RC uses the strict cement amount according to the current concrete code, but SFRSCC has a greater potential to improve, since the used cement content may be reduced by the addition of supplementary cementitious materials as stated in Subsection 3.1. For example, a reduction of 7% in cement (limiting it to 400 kg/m^3 for SFRSCC) will increase the indicator value up to 0.20 and the ESI up to 15%.

For the rest of indicators, any additional actions will similarly improve the results for both materials. For example both, SFRSCC and RC, can be mixed with recycled aggregates and therefore the difference due to the use of finer aggregates in the SFRSCC will remain. The reinforcement could also be optimised in case of using recycled fibres or rebars. This situation has not been considered in the methodology, but is more feasible to apply it to the fibre reinforcement as stated in (Pilakoutas et al., 2004) than in the RC rebars.

Although the high cement amount required for SFRSCC penalises considerably its environmental sensitivity, it is not always directly linked to a less sustainable alternative (Martin, 2004) (Pons and de la Fuente, 2013). Besides, SFRSCC favours other issues as durability and social questions. Studying the last three indicators, linked to these social issues, it can be observed that SFRSCC reduces the exposure of workers to several risks. On the one hand, the time required for certain hazardous labours, such as rebar handling and casting, is minimised and on the other hand, the high quality of the concrete avoids the need for subsequent additional repair works. The methodology also focuses the interest in developing NDT methods to characterise the mechanical properties and reduce the waste generated due to quality control tests.

5.2. Economic comparison

It is obvious that concrete costs increase for an SCC solution, as larger amounts of cement and superplasticiser make it more expensive; a common RC is approximately 43% cheaper. However, exposure of the structure to an aggressive environment of waster-water treatment systems means that the category that is adopted will require a larger volume of cement for RC, closer to that of the SCC, which reduces the aforementioned difference to 13%. This increase in the cost of concrete arises from the consequences of changes to the procedures established in the mixing plant. This leads to the need to train workers and to invest in equipment, and mainly to control the humidity of the raw materials, enabling the optimised production of a more challenging concrete.

Although the price of steel is more prone to fluctuations, one ton of steel fibre tends to cost 18% more than one ton of traditional rebars. However, the greatest benefits of the fibres are evident in surface elements of reduced thickness, such as slabs and walls. These sorts of elements are usually reinforced above their structural requirements due to shrinkage issues during hardening and curing. The effectiveness of fibres at early stages allows the reduction of that steel amount (29% less), counteracting their higher cost. As mentioned above, recycled fibres will definitively minimise the cost of the reinforcement (Pilakoutas et al., 2004)

Figure 11 illustrates the construction cost per cubic metre (€/m^3) of a 3 metres-high and 0.25 metres-width concrete wall for both alternatives. The first five stacked bars correspond to the main concrete components, cement, water, gravel, sand and admixtures, while the following match with the steel, its handling, the necessary formwork and the casting, respectively. As stated above, the higher cost of cement and admixtures lead to a more expensive concrete. Note that the cost of the water is not appreciable in the plot since it is negligible in comparison with the rest. The steel also presents a slightly higher cost, although counterbalanced by the reduced steel amount. However, those negative issues are counteracted by simplifying the construction work. Furthermore, the synergy between SFRC and SCC materials entails a noticeable time reduction in rebar mesh assemblies and overlaps, especially for complex geometries, as well as concrete pouring and placing (65% less).

Although the final cost of the SFRSCC alternative remains marginally above the RC cost, it must be noted that other positive intangible issues are hidden behind that handling and casting time reduction. However, constructors are often unwilling to attach importance to this issue, as they have an interest in keeping their

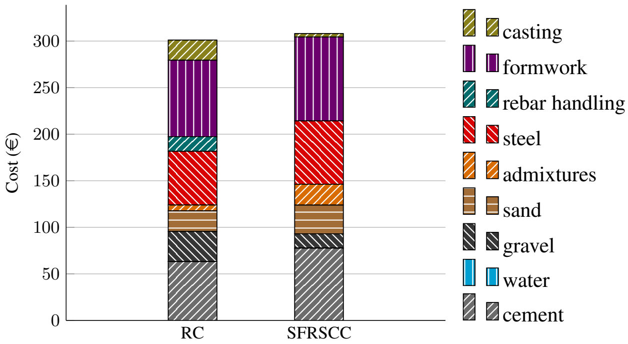

Figure 11. Cost of retaining tank wall (€/m^3)

employees engaged in on-site activities. Unfortunately, constructors are usually unaware of the expense that an occupational accident can entail. This time minimisation, in addition to direct reductions in costs, also results in a lower probability of accidents and in possible economic savings. According to Eurostat (statistical office of the European Union) (EUROSTAT, 2016), in 2013 Spain suffered 37,623 work-related accidents in the construction sector, while Germany had 105,132, France 86,211, Italy 37,863 and the UK 24,119. During 2015, 47228 total accidents (46596 ill health, 556 injuries and 76 fatal injuries) were registered in the construction sector in Spain, with a prevalence rate of 6573,9 (per 100000 workers) (EAT, 2015). The cost of occupational accidents not only have repercussions on individuals and employers but also on the society. These costs, could be further subdivided in non-financial human costs and financial costs and also in private cost and social costs. The estimated average appraisal values for fatal injuries is 1,575,000 £, 880 and 27,700 £ for up to 6 days of absence and 7 or more days of absence respectively, in case of non-fatal injuries and 850 and 37,400 £ in the event of ill health, with up to 6 and 7 or more days of absence respectively (HSE, 2015). Therefore, the cost of non-security may cause high costs in alternatives that, a priori, seem more favourable.

6. Conclusions

The paper has presented a methodological approach to multiple-criteria decision-making for structural material selection. Since the MIVES methodology has been successfully applied in numerous areas, the Spanish Structural Steel and Concrete Codes have adopted this tool for the sustainability assessment of structures. Among the established criteria, besides the environmental impact of the materials and their economic cost, the inclusion of worker safety and construction work hazards should be highlighted. The ease of rearranging the different indicators to different case studies makes this methodology a valuable tool.

This study of a real-scale structural element has presented a comparison of both the economic benefits and the improved sustainability of the SFRSCC for waste-water treatment systems as against traditional technologies and systems. Developmental research and advances must be accompanied by evidence of the benefits that their incorporation in the construction sector would bring to the market. The study has presented a quantification of these advantages in aggressive exposure classes, which complements previous studies that have discussed them in qualitative terms. The methodology highlights the notorious influence of mixed cement amount on the sustainable performance. RC can be mixed with the strict required cement amount, while SFRSCC requires a higher dosage to achieve self-compactability properties. Although in aggressive exposures the cement demand of RC is increased to closer values to that of the SFRSCC, the latter is markedly penalised by the corresponding indicator. However, SFRSCC favours other social issues that allow to improve its final sustainable contribution. Moreover these advantages would imply an Environmental Sensitivity Index (ESI) for SFRSCC that is 7.5% higher than for conventional RC, while overall costs would remain similar and the construction time frame could be greatly reduced by as much as 65%. Rebar processing and handling work is totally suppressed and casting process becomes simpler pumping the concrete at once, with no need to cast tiers of small thickness nor its vibration. This time reduction contribute to balance the increase of the cost of the materials, specially cement and admixtures. In addition, there are intangible benefits linked to short periods of construction among which the potential reduction of occupational accidents is noteworthy.

Future research should focus on achieving self-compactability properties with lower cement amounts, by the addition of other cementitious composites, since SFRSCC has still room for improving its Environmental Sensitivity Index. The use of any kind of recycled raw materials, aggregates or reinforcement, is also interesting. In addition to the indicators related to materials consumption, the improvement of safety of workers, waste reduction and other social issues must be enhanced. Research must be intensified on systems that reduce the exposure of workers to harmful materials and hazards and the residents to traffic and noise disturbances.

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Figure 1. Relation and hierarchy of the indicators

Figure 2. Value function for optimising cement

Figure 3. Value function for optimising aggregate size

Figure 4. Value function for optimising mixing water

Figure 5. Value function for optimising the quantity of admixtures

Figure 6. Value function for optimising the reinforcement

Figure 7. Value function for impact control

Figure 8. Value function for construction time

Figure 9. Value function for optimising generated waste

Figure 10. Comparison between both case studies

Figure 11. Cost of retaining tank wall (€/m3)