CONCRE*Top* method: Optimization of concrete with various incorporation ratios of fly ash and recycled aggregates in terms of quality performance and life-cycle cost and environmental impacts

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Abstract: This study shows how to optimize traditional and non-traditional concrete mixes from various perspectives, specifically technical performance (e.g. mechanical and durability characteristics), and economic (cost) and environmental (e.g. global warming and energy consumption) life cycle. Firstly, the weight to be considered for each of these perspectives (dimensions) of performance depends on the concrete application and on the user's requirements. In this study, concrete mixes containing various amounts of recycled concrete aggregates (RCA) and/or fly ash (FA) are optimized for different applications in the construction sector, namely high-rise building, sustainable residential housing, economical residential housing and residential housing close or far from the sea. For that purpose, the CONCRE***Top*** (a multi-criteria decision method for concrete optimization) methodology (developed by the authors of this study) was applied to these concrete mixes by considering the global requirement scenarios (e.g. cost, strength, green, service life and business as usual) that are normally demanded by users. This study is an example of CONCRE***Top***'s application and also contributes to its validation. The results show that, for all applications and scenarios that users may demand, the optimum concrete mixes in terms of concrete characteristics, cost and environmental impact are the ones produced with both FA and RCA incorporation, rather than their individual incorporation. This study shows that CONCRE***Top*** is straightforward in its application, i.e. it does not require excessive time and resources, and is focused on the final output, where the selection of the optimal concrete mixes can be directly used by the user, avoiding therefore lengthy inventory analysis and modifications.

Keywords: Optimum concrete; multi-criteria analysis; quality performance; Life Cycle Assessment; costs; environmental impacts.

1 Introduction

It has been reported by many studies that concrete has a significant influence on environmental impacts (EI) because it is one of the most widely used materials worldwide. For that purpose, researchers have proposed many alternative ways to decrease the EI of concrete and also mortars, e.g. by incorporating construction demolition wastes (Akhtar and Sarmah, 2018; Bertelsen et al., 2016; Bravo et al., 2017; Pacheco et al., 2015; Pedro et al., 2017; Silva et al., 2016; Thomas et al., 2018a; Tošić et al., 2015) and/or cementitious materials (Marinković et al., 2017; Sigvardsen and Ottosen, 2016; Sigvardsen and Ottosen, 2019; Silva and de Brito, 2016; Xie et al., 2019; Wang et al., 2017; Zhang et al., 2019) in concrete. Even though the effect of alternative materials on concrete has been extensively studied from different perspectives, e.g. quality performance (fresh and hardened states) and life-cycle cost and environmental impacts (Damdelen, 2018; Göswein et al., 2018; Nakic, 2018; Thomas et al., 2018b; Younis et al., 2018), there is still a huge gap between the mentioned perspectives due to the indirect relationship between them. In other words, most of the studies considered only one perspective, e.g. quality performance or Life Cycle assessment (LCA). In fact, there are some studies focusing on multiple perspectives but it is difficult to optimize and make the connection between the concrete mixes (CM) and the various characteristics and perspectives because of (i) dissimilar conditioning units for each characteristic, and (ii) changing weights of each characteristic based on the concrete's application. Besides, (iii) the best performing concrete mixes may be identified but they still may not be considered the optimal concrete mixes (OCM), e.g. a high strength concrete mixes may not be the best feature for residential housing due to its high cost.

The OCM cannot be defined considering a single perspective. In other words, the OCM are not necessarily the ones with the lowest EI (low LCA) or highest quality performance (high service life) or lowest cost. Exemplifying, it is possible to produce a lower EI concrete than that of traditional concrete by incorporating non-traditional materials (e.g. recycled concrete aggregates - RCA). Nevertheless, the concrete mixes with non-traditional materials may not be a sustainable solution if its service life is far lower than that of the conventional concrete (Kurad et al., 2017; Kurda et al., 2018a). A similar reasoning can be established when the quality performance of concrete compares with its cost. For example, one can produce concrete with lower cost than that of traditional concrete by using non-traditional materials (e.g. fly ash - FA). However, the concrete with non-traditional materials is not necessarily an economical option because the cross-section of the structure elements made with this concrete may need to be increased and additional material be consumed to attain an equal load capacity to that of the conventional concrete (Silva et al., 2016). Thus, it is important to consider all the perspectives to optimize the concrete mixes for any application and required scenario. Additionally, non-conventional materials (e.g. FA and RCA) can only be considered environmentally friendly when they do not significantly jeopardize the quality (service life) of concrete.

Apart from the reasons above, concrete mixes with various incorporation ratio of both FA and RCA are optimized in order to show the construction industry their effects on sustainability and also their applicability (performance) in different applications. In addition, the previous researchers that made an extensive literature on this area (Verian et al., 2018; Kurda et al., 2017) show that there are many studies related to the individual effect of FA or RCA but few studies related to the combined effect of both materials on concrete. Furthermore, most of the researchers studied the effect of high incorporation ratio of RA and FA from one viewpoint only (e.g. EI or quality or cost) of concrete.

To overcome this issue, the authors of this study proposed a novel method (CONCRE***Top*** - A multi-criteria decision method for concrete optimization - (Kurda et al., 2019a)) to choose the optimum out of 28 concrete mixes according to the quality performance, EI and cost. In the present study, concrete mixes containing various amounts of RCA and/or FA are optimized to be used in different applications (e.g. high-rise building, sustainable residential housing, economical residential housing and residential housing close or far from the sea). For that purpose, the mentioned methodology was applied to these concrete mixes by considering different scenarios (cost, strength, green, service life and business as usual). This study is an example of CONCRE***Top***'s application and also contributes to its validation. Finally, the aim of testing various applications is to show the reliability of the mentioned method in any scenario and application within the construction industry.

2 Materials and methods

As mentioned before, the aim of this study is to optimize concrete mixes with various incorporation ratios of FA and/or RCA from the perspectives of quality performance, cost and EI simultaneously. To that end, the CONCRE***Top*** method (Kurda et al., 2019a) was used (§3) to select the OCM.

2.1 Method

Following the presentation of the CONCRE***Top*** methodology made in the scope of the previous study of the authors (Kurda et al., 2019a), this work presents examples of the CONCRE***Top*** methodology's application to certify and validate it. Thus, in §3, twenty eight CM, whose characteristics were studied before by the authors, were analysed to find the OCM for each of five applications. According to the method, seven steps need to be followed in order to reach the final decision (Figure 1).

The OCM can only be identified after simultaneous optimization from the perspectives of EI, quality performance and economic cost. Furthermore, the OCM also depends on its application and users demands, because the weight (importance) to be considered for each of these dimensions (perspectives) of concrete performance depends on the same parameters. Therefore, this study considered 5 applications (economical residential housing, high-rise building, sustainable residential housing, and residential housing close and far to the sea) of the concrete mixes (their mix compositions are shown below) with the most probable scenarios that the construction sector (cost, strength, green, business as usual and service life) may demand.

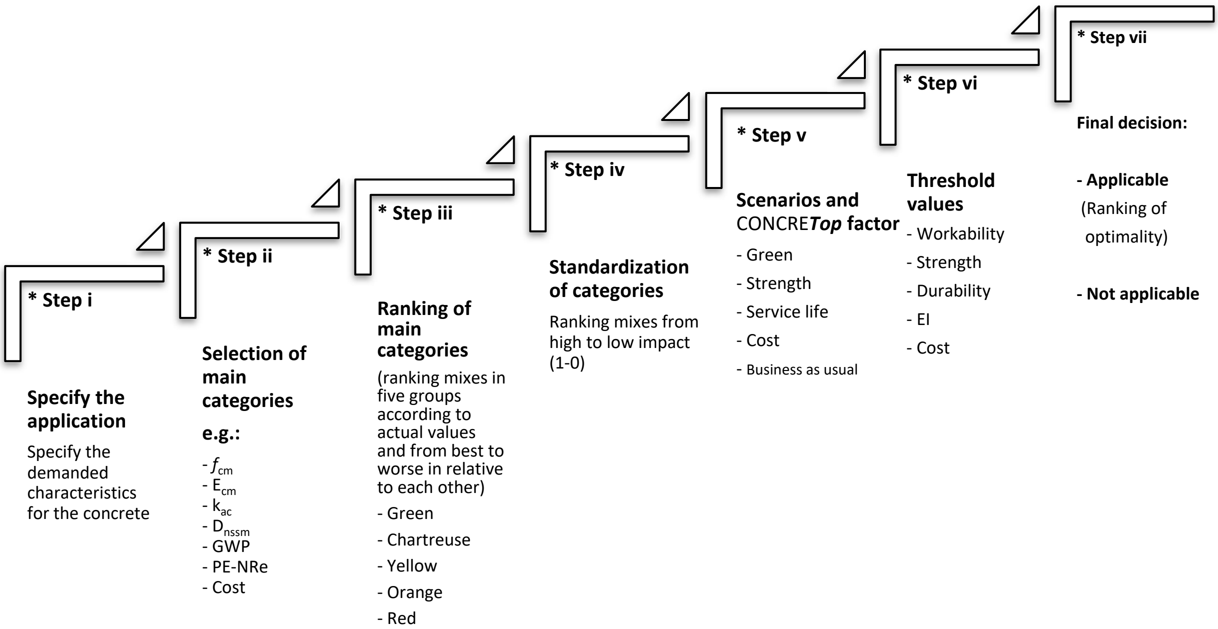

Figure 1 - Profile of the CONCRE***Top.*** Each step was explained in detail in Kurda et al. (Kurda et al., 2019a)

2.2 Materials and concrete composition

The concrete mixes are made with ordinary Portland cement (CEM 42.5 R - OPC) and FA (type F), fine and coarse RCA (aggregates made with 100% of uncontaminated crushed concrete), and fine (natural silica sand) and coarse (crushed limestone) natural aggregates (NA). The binder content (FA and OPC) is kept constant in all concrete mixes (350 kg/m^3). Workability is also kept constant (S2). Superplasticizer (SP) is used in almost half of the mixes in order to understand its effect on their quality, cost and EI. The water to binder ratio (w/b) of traditional concrete without (M1) and with ($M1_{sp}$) SP (1% of binder's weight) was 0.53 and 0.42, respectively. Various amount of FA, fine RCA and coarse RCA with and without SP are used in the concrete mixes (Table 1). The mix composition and the properties the materials are briefly explained in order to avoid repetition, because the details regarding the materials properties, mix design, mixing procedure of the concrete mixes are already shown in previous works of the same authors (Kurad et al., 2017).

2.3 Main categories

Quality performance (e.g. compressive strength, modulus of elasticity, carbonation and chloride ion penetration resistances), EI (GWP and PE-NRe) and cost (Table2) of the concrete mixes (Table 1) were determined experimentally and analytically, and compared in following the steps of CONCRE***Top*** (§3).

Further details regarding each test are shown in Table 2.

Table 1 - Concrete mixes composition

RCA %vol	Coarse RCA	0			100		
	Fine RCA	0	50	100	0	50	100
FA %wt	0	M1 & $M1_{sp}$	M2	M3 & $M3_{sp}$	M10 & $M10_{sp}$	M11	M12 & $M12_{sp}$
	30	M4	M5 & $M5_{sp}$	M6	M13	M14 & $M14_{sp}$	M15
	60	M7 & $M7_{sp}$	M8	M9 & $M9_{sp}$	M16 & $M16_{sp}$	M17	M18 & $M18_{sp}$

Table 2 - Standards and details for each selected category

Categories	Abbreviation	Units	Test specimen size	Standard	Further details
Compressive strength	$f_{cm,cube}$	MPa	150x150 mm	(EN 12390-3, 2009)	Kurad et al. (2017)
Modulus of elasticity	E_{cm}	GPa	Ø150x300 mm	(LNEC E 397, 1993)	Kurda et al. (2018b)
Carbonation	K_{ac}	mm	Ø150x40 mm	(LNEC E 391, 1993)	Kurda et al. (2019b)
Chloride ion penetration	D_{nssm}	m^2/s	Ø150x50 mm	(LNEC E463, 2004; Nordtest BUILD NT, 1999)	Kurda et al. (2018a)
Cost	-	Euros	Cubic meter	-	Kurda et al. (2018b)
Global warming potential	GWP	kg CO_2 eq	Cubic meter	LCA methodology (EN 15804, 2012; ISO 14040, 2006)	Kurad et al. (2017)
Non-renewable primary energy resources	PE-NRe	MJ	Cubic meter	LCA methodology (EN 15804, 2012; ISO 14040, 2006)	Kurda et al. (2018a)

In terms of the life-cycle economic and environmental assessment, the most plausible scenarios for the Lisbon region in Portugal (Figure 2) from cradle to gate (A1-A3) based on EN 15804 (2012) and ISO 14040 (2006) were used to obtain the EI and cost of each concrete mixes (Table 2).

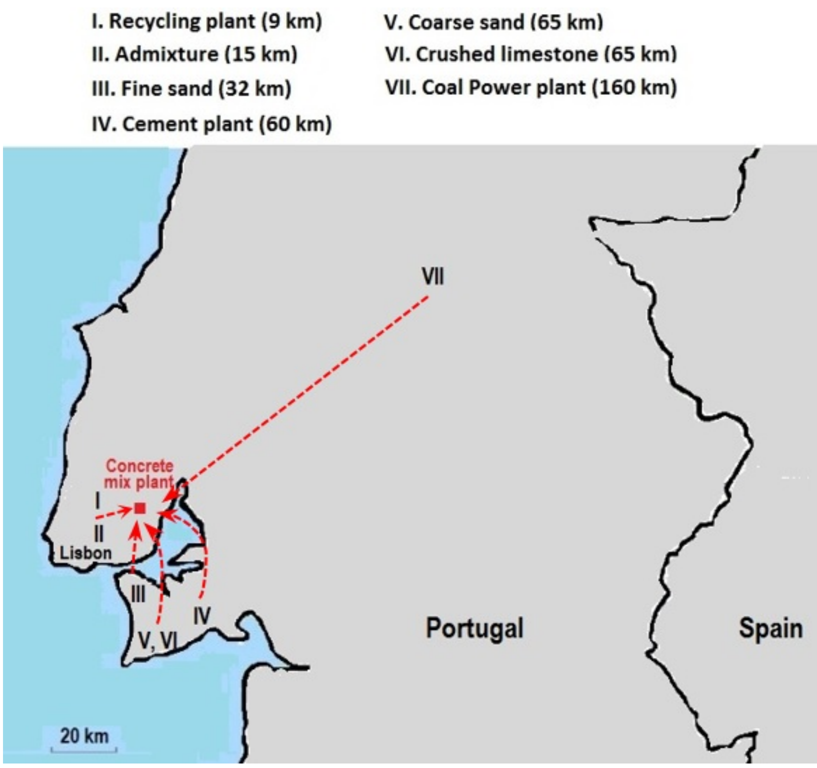

Figure 2 - Most common transportation scenario in the Lisbon region (Portugal)

Similarly to other studies (Zhang et al. 2019; Marinković et al. 2017), the life cycle inventory was sourced from different studies due to lack of site specific data. Thus, the final output of the LCA may be affected by these choices. These results are deterministic, since no information on uncertainty was found in each source. Moreover, a sensitivity analysis of the consequences on the results of selecting different sources to model the life-cycle of each mix is out of the scope of this paper. Additionally, it is necessary to consider the uncertainty factor for the LCA and quality performance of the non-conventional materials (e.g. FA and RCA). For example, the EI of concrete (1 m^3) may decrease with the incorporation of FA while the standard deviation of all results increases. This issue may be considered as a limitation of this work. Therefore, the authors suggest considering the methodology proposed by the study of Zhang et al. (2018), especially after step iii (§3.3), to overcome this issue.

3 Application of CONCRETop to the concrete mixes of this study

3.1 Specification of the application (step i)

Since the optimization process essentially depends on the "application of concrete" and the "specific characteristics" that may be demanded by the user, the application of the concrete mixes and scenario need to be identified first. In this study five different applications (§2.1) are considered to cover the most frequent uses of concrete in the construction sector. Moreover, to be close to the reality of the construction sector, the specific boundaries (e.g. the specific value of the compressive strength that may be demanded by users) for each selected application are identified. For such a complex case as this, the CONCRE***Top*** method identified specific boundaries to optimize the concrete mixes based on the users' demand by using different scenarios. In addition, the scenarios were selected based on the application, i.e. based on common sense and basic experience in the construction sector. For example, for conventional residential housing, the cost and strength of concrete are the main factors demanded by users. Therefore, the "business as usual" scenario was considered to optimize the CM. For the other applications, e.g. for the economical residential housing, high-rise building, sustainable residential housing and residential housing close to the sea, the cost (cost scenario), strength (strength scenario), EI (green scenario) and durability (service life scenario) are the most important factors, respectively. In addition, for each application of concrete, the concrete mixes were optimized for the same structural behaviour and code expressions (e.g. applied load, weather, concrete cover, cross-section of concrete member and area of reinforcement).

3.2 Selection of main categories (step ii)

For this stage, the essential properties of concrete mixes were chosen based on step ii from Kurda et al. (2019a). First, for fresh properties, the workability of concrete, namely slump, was considered for all concrete mixes. For the hardened state, the compressive strength and modulus of elasticity for mechanical properties, and chloride ion penetration (non-steady state chloride migration coefficient of diffusion) and carbonation resistances for durability, were selected for each mix composition. Regarding the durability performance of the concrete mixes, although it would be more reliable to optimize the concrete mixes based on the “complex functional unit - service life impacts” (calculated by considering several parameters, e.g. temperature, relative humidity, drying-wetting cycles, chloride concentration) than that of the “complex functional unit - durability parameters” (Hafez et al., 2019), the CONCRE***Top*** method also allows to optimize concrete mixes by considering the “complex functional unit - durability parameters” when the service life is not calculated. In other words, apart from the fact that the weight (importance) of the durability parameters depend on the concrete application, the method also considered the threshold values proposed by study of Gjørv (1996) to make a relationship between the durability parameter (e.g. D_{nssm}) and its service life.

Furthermore, this study considered Dnssm as one of the durability indicator without considering the effect of convection zone (distance from the surface) and peak value of chloride concentration (which were not measured in the experimental campaign performed). This indicator would be more reliable if the mentioned factors were considered (Zhang et al., 2019). Although the mentioned factors may affect the durability results, the optimization process based on the CONCRETop method does not change because the method standardizes the value and optimizes the mixes based on the value relative to conventional concrete.

Both selected mechanical and durability properties were considered at early (28 days) and longer (365 days) ages. Furthermore, the PE-NRe and GWP were selected for LCA as well as the cost of 1 m^3 of each concrete (Figure 3).

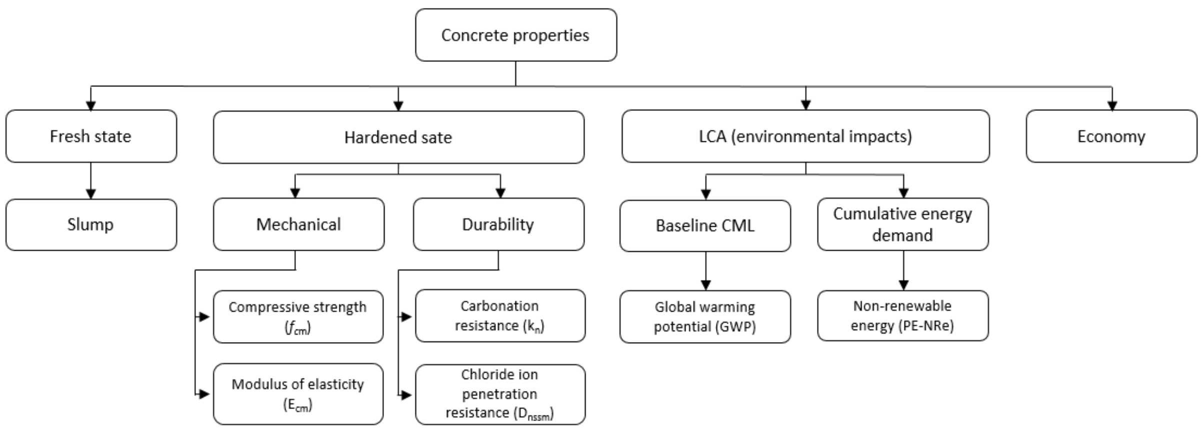

Figure 3 - Main categories that can be used in the optimization

3.3 Ranking of main categories (step iii)

For this stage, the concrete mixes are ranked by colour based on step iii from Kurda et al. (2019a), as in Table 3. The colours assigned correspond to five intervals, as explained in the footnotes of Table 3, each one covering 20% of the difference between the worst and the best results for each characteristic of the concrete mixes that are compared. The main objective of this step is to compare the actual results and to have a general idea about all CM. First, the results of each characteristic are expressed in five colours, and then each property of all selected concrete mixes was ranked.

Table 3 - Ranking of concrete mixes of this study based on the actual value of each property

concrete mixes [a]	FA (%)	Fine RCA (%)	Coarse RCA (%)	SP (%)	Slump (cm)	$f_{cm,cube}$ (MPa)		E_{cm} (GPa)		D_{nssm} ($\times 10^{-12} m^2/s$)		Carbonation "k_{ac}" (mm $year^{0.5}$)	GWP (kg CO_2 eq)	PE-NRe (MJ)	Cost (€/m^3)
						28 days	365 days	28 days	365 days	28 days	365 days				
M1	0	0	0	0	7.3	55.8	61.3	43.8	47.0	12.6	7.9	11.30	361.6	1949.5	79.9
M2	0	50	0	0	8.7	46.2	52.0	39.0	41.4	15.0	9.3	18.70	360.7	1941.8	78.3
M3	0	100	0	0	8.1	45.0	51.5	34.7	39.0	16.2	9.8	26.90	360.0	1936.2	76.7
M4	30	0	0	0	8.6	40.2	60.0	41.4	50.3	8.1	2.9	33.73	268.7	1579.3	72.6
M5	30	50	0	0	8.3	36.4	57.2	38.3	46.3	8.9	3.0	37.70	267.9	1572.2	71.0
M6	30	100	0	0	7.5	34.0	54.2	32.4	43.2	9.7	3.1	49.52	267.0	1564.3	69.4
M7	60	0	0	0	7.2	24.0	42.2	38.0	46.1	11.2	3.1	61.58	175.9	1209.7	65.3
M8	60	50	0	0	7.5	23.6	42.5	34.1	41.8	11.8	3.2	63.30	174.2	1190.1	63.6
M9	60	100	0	0	8.5	21.5	40.0	32.3	41.4	13.2	3.3	66.40	174.2	1194.5	62.2
M10	0	0	100	0	7.6	51.9	59.2	37.1	41.4	14.0	8.5	15.35	331.1	1528.6	74.6
M11	0	50	100	0	8.9	42.8	51.0	32.5	36.3	16.8	10.0	26.10	330.7	1526.6	73.1
M12	0	100	100	0	8.1	42.0	50.2	28.0	31.4	18.1	10.6	30.30	330.3	1525.4	71.6
M13	30	0	100	0	8.9	39.0	62.0	34.8	42.8	8.5	3.0	39.90	238.1	1155.8	67.3
M14	30	50	100	0	8.8	33.0	56.6	32.5	40.0	9.3	3.2	42.30	237.6	1153.9	65.8
M15	30	100	100	0	8.3	32.8	53.4	29.7	38.3	10.0	3.3	49.56	237.2	1151.9	64.3
M16	60	0	100	0	8.6	23.0	41.0	33.0	41.1	11.9	3.2	59.80	145.0	783.1	59.9
M17	60	50	100	0	8.8	21.1	38.8	29.4	36.7	12.5	3.4	64.00	144.6	781.1	58.4
M18	60	100	100	0	7.3	21.0	38.0	26.9	35.3	14.2	3.6	66.30	144.2	779.1	57.0
$M1_{sp}$	0	0	0	1	8.5	73.5	83.0	51.4	55.7	6.4	3.9	1.60	364.0	1983.2	90.1
$M3_{sp}$	0	100	0	1	8.8	54.1	63.7	39.9	42.6	9.4	5.5	7.80	362.5	1970.8	86.7
$M5_{sp}$	30	50	0	1	8.9	60.4	79.0	43.9	50.2	4.2	1.0	4.20	270.3	1605.6	81.1
$M7_{sp}$	60	0	0	1	8.1	42.4	58.0	40.7	47.7	5.4	1.1	59.84	178.7	1248.1	75.5
$M9_{sp}$	60	100	0	1	8	37.1	57.0	34.4	42.0	6.6	1.3	51.83	176.6	1228.5	72.1
$M10_{sp}$	0	0	100	1	8.8	63.0	73.0	43.5	47.7	7.6	4.6	1.50	331.8	1538.2	84.5
$M12_{sp}$	0	100	100	1	8.9	49.0	60.6	33.9	35.8	10.6	6.1	9.00	331.0	1534.9	81.2
$M14_{sp}$	30	50	100	1	8.7	53.8	74.0	38.3	44.0	4.6	1.1	12.20	238.3	1163.4	75.5
$M16_{sp}$	60	0	100	1	8.8	38.0	59.0	38.3	43.6	5.9	1.2	57.10	145.7	792.6	69.8
$M18_{sp}$	60	100	100	1	8.9	32.3	54.0	30.1	35.5	7.3	1.4	44.00	144.8	788.7	66.6

[a] For each property (each column), the colours green, chartreuse, yellow, orange and red present very high, high, medium, low and very low performances in relation to all selected mixes. **Bold** mixes are expected to be OCM for most scenarios.

By comparing the characteristics of the CM, the results shows that green and yellow are the most frequent colours for the following CM, namely by incorporating: 30% of FA without (M4) or with (M13) 100% of coarse RCA; both 30% of FA and 50% of fine RCA either without or with 100% of coarse RCA (M5 and M14) and SP ($M5_{sp}$ and $M14_{sp}$); 60% of FA and SP without ($M7_{sp}$) and with ($M16_{sp}$) 100% of coarse RCA (Table 3). Thus, it can be said that most of the concrete properties of the mentioned concrete mixes are between "medium" and "very good" relative to other CM. In spite of the fact that the optimization of concrete depends on the selected scenarios and application of concrete, in general, the following concrete mixes can be selected as having better concrete performances for most of the concrete properties. In fact decisions made based only on this step may not be reliable, but it is necessary to show them in order to understand how each criterion works.

3.4 Standardization of categories (step iv)

The characteristic values of concrete mixes are standardized based on step iv from Kurda et al. (2019a). As mentioned before, in order to optimize various concrete mixes with different characteristics, the measured units for each property should be, as much as possible, the same. Therefore, the numbers were homogenised from 0 to 1. Then, the concrete mixes were sorted from best to worst performing based on each characteristic (Table 4). In addition, the results are ordered and categorized in five colours based on§3.3.

Table 4 - Ranking and standardization of concrete mixes of this study

f_{cm} (28 days)		f_{cm} (365 days)		E_{cm} (28 days)		E_{cm} (365 days)		D_{nssm} (28 days)		D_{nssm} (365 days)		K_{ac}		GWP		PE-NRe		Cost	
M1sp	1.00	M1sp	1.00	M1sp	1.00	M1sp	1.00	M5sp	1.00	M5sp	1.00	M10sp	1.00	M18	1.00	M18	1.00	M18	1.00
M10sp	0.80	M5sp	0.91	M5sp	0.69	M4	0.78	M14sp	0.97	M7sp	0.99	M1sp	1.00	M17	1.00	M17	1.00	M17	0.96
M5sp	0.75	M14sp	0.80	M1	0.69	M5sp	0.77	M7sp	0.91	M14sp	0.99	M5sp	0.96	M18sp	1.00	M16	1.00	M16	0.91
M1	0.66	M10sp	0.78	M10sp	0.68	M7sp	0.67	M16sp	0.88	M16sp	0.98	M3sp	0.90	M16	1.00	M18sp	0.99	M9	0.84
M3sp	0.63	M3sp	0.57	M4	0.59	M10sp	0.67	M1sp	0.84	M9sp	0.97	M12sp	0.88	M16sp	0.99	M16sp	0.99	M8	0.80
M14sp	0.62	M13	0.53	M7sp	0.56	M1	0.64	M9sp	0.83	M18sp	0.96	M1	0.86	M8	0.86	M15	0.69	M15	0.78
M10	0.59	M1	0.52	M3sp	0.53	M5	0.61	M18sp	0.78	M4	0.80	M14sp	0.84	M9	0.86	M14	0.69	M7	0.75
M12sp	0.53	M12sp	0.50	M2	0.49	M7	0.60	M10sp	0.76	M5	0.79	M10	0.80	M7	0.86	M13	0.69	M14	0.73
M2	0.48	M4	0.49	M5	0.47	M14sp	0.52	M4	0.72	M13	0.79	M2	0.74	M9sp	0.85	M14sp	0.68	M18sp	0.71
M3	0.46	M10	0.47	M14sp	0.47	M16sp	0.50	M13	0.69	M6	0.78	M11	0.64	M7sp	0.84	M8	0.66	M13	0.69
M11	0.42	M16sp	0.47	M16sp	0.47	M6	0.49	M5	0.66	M7	0.78	M3	0.62	M15	0.58	M9	0.66	M6	0.63
M7sp	0.41	M7sp	0.44	M7	0.45	M13	0.47	M14	0.63	M8	0.77	M12	0.57	M14	0.58	M7	0.64	M16sp	0.61
M12	0.40	M5	0.43	M10	0.42	M3sp	0.46	M3sp	0.63	M14	0.77	M4	0.53	M13	0.57	M9sp	0.63	M5	0.58
M4	0.37	M9sp	0.42	M13	0.32	M9sp	0.44	M6	0.60	M16	0.77	M5	0.47	M14sp	0.57	M7sp	0.61	M12	0.56
M13	0.34	M14	0.41	M3	0.32	M8	0.43	M15	0.58	M9	0.76	M13	0.44	M6	0.44	M12	0.38	M9sp	0.54
M16sp	0.32	M6	0.36	M9sp	0.31	M2	0.41	M12sp	0.54	M15	0.76	M14	0.40	M5	0.44	M11	0.38	M4	0.53
M9sp	0.31	M18sp	0.36	M8	0.29	M9	0.41	M7	0.50	M17	0.75	M18sp	0.37	M4	0.43	M10	0.38	M11	0.51
M5	0.29	M15	0.34	M12sp	0.29	M10	0.41	M8	0.45	M18	0.73	M6	0.30	M5sp	0.43	M12sp	0.37	M10	0.47
M6	0.25	M2	0.31	M16	0.25	M16	0.40	M16	0.45	M1sp	0.70	M15	0.30	M12	0.15	M10sp	0.37	M7sp	0.44
M14	0.23	M3	0.30	M11	0.23	M14	0.35	M17	0.40	M10sp	0.63	M9sp	0.27	M11	0.15	M6	0.35	M14sp	0.44
M15	0.22	M11	0.29	M14	0.23	M3	0.31	M1	0.40	M3sp	0.53	M16sp	0.16	M12sp	0.15	M5	0.34	M3	0.40
M18sp	0.22	M12	0.27	M6	0.22	M15	0.28	M9	0.35	M12sp	0.47	M7sp	0.14	M10	0.15	M4	0.34	M2	0.36
M7	0.06	M8	0.10	M9	0.22	M17	0.22	M10	0.29	M1	0.28	M16	0.12	M10sp	0.15	M5sp	0.31	M1	0.31
M8	0.05	M7	0.09	M18sp	0.13	M11	0.20	M18	0.28	M10	0.22	M7	0.09	M3	0.02	M3	0.04	M5sp	0.27
M16	0.04	M16	0.07	M15	0.11	M12sp	0.18	M2	0.22	M2	0.14	M8	0.06	M2	0.02	M2	0.03	M12sp	0.27
M9	0.01	M9	0.04	M17	0.10	M18sp	0.17	M3	0.14	M3	0.08	M17	0.06	M1	0.01	M1	0.03	M10sp	0.17
M17	0.00	M17	0.02	M12	0.04	M18	0.16	M11	0.09	M11	0.06	M18	0.01	M3sp	0.01	M3sp	0.01	M3sp	0.10
M18	0.00	M18	0.00	M18	0.00	M12	0.00	M12	0.00	M12	0.00	M9	0.00	M1sp	0.00	M1sp	0.00	M1sp	0.00

3.5 Scenarios and CONCRETop factor (step v)

For this stage, the scenarios were set according to step v from Kurda et al. (2019a), specifically "green", "cost", "service life", "business as usual" and "strength" scenarios for sustainable residential housing, economical residential housing, residential housing close to the sea, residential housing far from the sea and high rise building, respectively. The weight of each category (cost, D_{nssm}, K_{ac}, f_{cm}, E_{cm}, GWP and PE-NRe) is identified based on the chosen scenario. In order to do so, the "CONCRE***Top*** factor" equation (Kurda et al., 2019a) is applied to optimize all the concrete mixes based on the chosen scenario and the results (CONCRE***Top*** value) are categorised in five colours based on §3.3. Tables 5 and 6 present the result of the optimization of the concrete mixes based on each scenario ranked by their concrete mixes number ($M1_{\text{with and without SP}}$-$M18_{\text{with and without SP}}$) and CONCRE***Top*** factor (1-0), respectively. The lower values identify the worst concrete mixes for each scenario, and the opposite occurs for higher values. Concrete mixes with better performances in §3.3 (the concrete mixes with green and yellow colours) show similar behaviour in this step for all scenarios. In addition, some other concrete mixes may be considered to have good performances based on this step. However, the "final decision" for each scenario can be only decided after the mix comparison with threshold values.

Table 5 - Optimizing the concrete mixes of this study for each scenario based on the CONCRETop factor (according to their mix number)

Concrete mixes [a &b]	Scenarios				
	Business as usual	Strength	Service life	Green	Cost
M1 (F0C0FA0)	0.531	0.432	0.482	0.223	0.385
M2 (F50C0FA0)	0.450	0.329	0.414	0.207	0.334
M3 (F100C0FA0)	0.426	0.320	0.378	0.211	0.341
M4 (F0C0FA30)	0.494	0.532	0.560	0.467	0.529
M5(F50C0FA30)	0.469	0.502	0.547	0.472	0.524
M6 (F100C0FA30)	0.428	0.466	0.495	0.469	0.514
M7 (F0C0FA60)	0.399	0.429	0.479	0.651	0.540
M8 (F50C0FA60)	0.398	0.429	0.481	0.667	0.556
M9 (F10C0FA60)	0.381	0.413	0.466	0.669	0.558
M10 (F0C100FA0)	0.536	0.457	0.517	0.379	0.459
M11 (F50C100FA0)	0.449	0.361	0.433	0.359	0.410
M12 (F100C100FA0)	0.432	0.341	0.408	0.361	0.410
M13 (F0C100FA30)	0.515	0.585	0.598	0.629	0.619
M14 (F50C100FA30)	0.480	0.536	0.584	0.629	0.603
M15 (F100C100FA30)	0.471	0.508	0.556	0.629	0.597
M16 (F0C100FA60)	0.443	0.473	0.554	0.819	0.629
M17 (F50C100FA60)	0.426	0.445	0.535	0.821	0.625
M18 (F100C100FA60)	0.420	0.441	0.528	0.828	0.635
M1sp (F0C0FA0SP)	0.589	0.590	0.550	0.190	0.390
M3sp (F100C0FA0SP)	0.448	0.384	0.477	0.168	0.295
M5sp (F50C0FA50SP)	0.599	0.658	0.693	0.452	0.535
M7sp (F0C0FA60SP)	0.431	0.492	0.465	0.587	0.482
M9sp (F100C0FA60SP)	0.431	0.500	0.530	0.626	0.523
M10sp (F0C100FA0SP)	0.562	0.542	0.590	0.343	0.425
M12sp (F100C100FA0SP)	0.455	0.400	0.524	0.330	0.367
M14sp (F50C100FA30SP)	0.590	0.656	0.715	0.609	0.595
M16sp (F0C100FA60SP)	0.466	0.563	0.546	0.770	0.591
M18sp (F100C100FA60SP)	0.465	0.528	0.628	0.799	0.607

[a] **F** - fine RCA%, **C** - coarse RCA%, **FA** - fly ash% and **SP** - superplasticizer;
[b] According to § 4.6.3, **Bold** concrete mixes expected to have higher CONCRE**Top** factor relative to the other CM.

In this work, the rankings of concrete mixes based on the green and cost scenarios were very close. This is because incorporating RCA and FA linearly and simultaneously decreases concrete's cost and EI. The same behaviour can be seen for other scenarios, namely strength, business as usual and service life (Table 6).

3.6 Threshold values (step vi)

In this step, threshold values were set in the study of Kurda et al. (2019a) for each characteristic of concrete according to step vi proposed in the same study. In general, the loads applied in residential housing are very low, the service life is considered to be about 50 years and the same type of concrete is used for all members of the structure. Therefore, the durability and strength for foundations and for those structural members exposed to air are considered the same. Generally, for residential housing, low strength classes of concrete may be optimal because its price is not significant and it is possible to produce without any special technique or admixtures. However, the mentioned facts are not applicable to sustainable residential housing because the demanded characteristics of concrete are different from economical one. Contrary to residential housing, the strength of concrete should be high for high-rise buildings. Therefore, in this step, 5 scenarios, namely “business as usual”, “green”, “strength”, “service live” and “cost” are chosen for “residential housing far from the sea” (Table 7), “sustainable residential housing” (Table 8), “high-rise building” (Table 9), “residential housing close to the sea” (Table 10) and “economical residential housing” (Table 11), respectively, where the concrete mixes were ordered based on Table 5 and then the results are compared with the threshold values set by Kurda et al. (2019a). The concrete mixes that are applicable (i.e. which comply with the threshold values) were not presented in Tables 7-11. Further details (analysing each mix) are shown in appendices i-v, respectively.

Table 6 - Optimized concrete mixes for different scenario based on the CONCRETop factor (ranked according to CONCRETop factor)

Scenarios									
Business as usual [a]		Green [a]		Strength [a]		Service life [a]		Cost [a]	
M5sp (F50C0FA50SP)	0.60	M18 (F100C100FA60)	0.83	M5sp (F50C0FA50SP)	0.66	M14sp (F50C100FA30SP)	0.71	M18 (F100C100FA60)	0.63
M14sp (F50C100FA30SP)	0.59	M17 (F50C100FA60)	0.82	M14sp (F50C100FA30SP)	0.66	M5sp (F50C0FA50SP)	0.69	M16 (F0C100FA60)	0.63
M1sp (F0C0FA0SP)	0.59	M16 (F0C100FA60)	0.82	M1sp (F0C0FA0SP)	0.59	M18sp (F100C100FA60SP)	0.63	M17 (F50C100FA60)	0.62
M10sp (F0C100FA0SP)	0.56	M18sp (F100C100FA60SP)	0.80	M13 (F0C100FA30)	0.59	M13 (F0C100FA30)	0.60	M13 (F0C100FA30)	0.62
M10 (F0C100FA0)	0.54	M16sp (F0C100FA60SP)	0.77	M16sp (F0C100FA60SP)	0.56	M10sp (F0C100FA0SP)	0.59	M18sp (F100C100FA60SP)	0.61
M1 (F0C0FA0)	0.53	M9 (F10C0FA60)	0.67	M10sp (F0C100FA0SP)	0.54	M14 (F50C100FA30)	0.58	M14 (F50C100FA30)	0.60
M13 (F0C100FA30)	0.51	M8 (F50C0FA60)	0.67	M14 (F50C100FA30)	0.54	M4 (F0C0FA30)	0.56	M15 (F100C100FA30)	0.60
M4 (F0C0FA30)	0.49	M7 (F0C0FA60)	0.65	M4 (F0C0FA30)	0.53	M15 (F100C100FA30)	0.56	M14sp (F50C100FA30SP)	0.60
M14 (F50C100FA30)	0.48	M13 (F0C100FA30)	0.63	M18sp (F100C100FA60SP)	0.53	M16 (F0C100FA60)	0.55	M16sp (F0C100FA60SP)	0.59
M15 (F100C100FA30)	0.47	M15 (F100C100FA30)	0.63	M15 (F100C100FA30)	0.51	M1sp (F0C0FA0SP)	0.55	M9 (F10C0FA60)	0.56
M5(F50C0FA30)	0.47	M14 (F50C100FA30)	0.63	M5(F50C0FA30)	0.50	M5(F50C0FA30)	0.55	M8 (F50C0FA60)	0.56
M16sp (F0C100FA60SP)	0.47	M9sp (F100C0FA60SP)	0.63	M9sp (F100C0FA60SP)	0.50	M16sp (F0C100FA60SP)	0.55	M7 (F0C0FA60)	0.54
M18sp (F100C100FA60SP)	0.46	M14sp (F50C100FA30SP)	0.61	M7sp (F0C0FA60SP)	0.49	M17 (F50C100FA60)	0.54	M5sp (F50C0FA50SP)	0.54
M12sp (F100C100FA0SP)	0.46	M7sp (F0C0FA60SP)	0.59	M16 (F0C100FA60)	0.47	M9sp (F100C0FA60SP)	0.53	M4 (F0C0FA30)	0.53
M2 (F50C0FA0)	0.45	M5(F50C0FA30)	0.47	M6 (F100C0FA30)	0.47	M18 (F100C100FA60)	0.53	M5(F50C0FA30)	0.52
M11 (F50C100FA0)	0.45	M6 (F100C0FA30)	0.47	M10 (F0C100FA0)	0.46	M12sp (F100C100FA0SP)	0.52	M9sp (F100C0FA60SP)	0.52
M3sp (F100C0FA0SP)	0.45	M4 (F0C0FA30)	0.47	M17 (F50C100FA60)	0.44	M10 (F0C100FA0)	0.52	M6 (F100C0FA30)	0.51
M16 (F0C100FA60)	0.44	M5sp (F50C0FA50SP)	0.45	M18 (F100C100FA60)	0.44	M6 (F100C0FA30)	0.50	M7sp (F0C0FA60SP)	0.48
M12 (F100C100FA0)	0.43	M10 (F0C100FA0)	0.38	M1 (F0C0FA0)	0.43	M1 (F0C0FA0)	0.48	M10 (F0C100FA0)	0.46
M7sp (F0C0FA60SP)	0.43	M12 (F100C100FA0)	0.36	M7 (F0C0FA60)	0.43	M8 (F50C0FA60)	0.48	M10sp (F0C100FA0SP)	0.42
M9sp (F100C0FA60SP)	0.43	M11 (F50C100FA0)	0.36	M8 (F50C0FA60)	0.43	M7 (F0C0FA60)	0.48	M11 (F50C100FA0)	0.41
M6 (F100C0FA30)	0.43	M10sp (F0C100FA0SP)	0.34	M9 (F10C0FA60)	0.41	M3sp (F100C0FA0SP)	0.48	M12 (F100C100FA0)	0.41
M3 (F100C0FA0)	0.43	M12sp (F100C100FA0SP)	0.33	M12sp (F100C100FA0SP)	0.40	M9 (F10C0FA60)	0.47	M1sp (F0C0FA0SP)	0.39
M17 (F50C100FA60)	0.43	M1 (F0C0FA0)	0.22	M3sp (F100C0FA0SP)	0.38	M7sp (F0C0FA60SP)	0.47	M1 (F0C0FA0)	0.39
M18 (F100C100FA60)	0.42	M3 (F100C0FA0)	0.21	M11 (F50C100FA0)	0.36	M11 (F50C100FA0)	0.43	M12sp (F100C100FA0SP)	0.37
M7 (F0C0FA60)	0.40	M2 (F50C0FA0)	0.21	M12 (F100C100FA0)	0.34	M2 (F50C0FA0)	0.41	M3 (F100C0FA0)	0.34
M8 (F50C0FA60)	0.40	M1sp (F0C0FA0SP)	0.19	M2 (F50C0FA0)	0.33	M12 (F100C100FA0)	0.41	M2 (F50C0FA0)	0.33
M9 (F10C0FA60)	0.38	M3sp (F100C0FA0SP)	0.17	M3 (F100C0FA0)	0.32	M3 (F100C0FA0)	0.38	M3sp (F100C0FA0SP)	0.30

[a] **F** - fine RCA%, **C** - coarse RCA%, **FA** - fly ash% and **SP** - superplasticizer.

Table 7 - Optimizing concrete mixes for residential housing in the "BUSINESS AS USUAL" scenario

Ranked CM	CONCRE***Top*** factor	Threshold	Applicable	Reasons
M1sp F 0% C 0% FA 0% SP 1%	0.562	Strength = 55/67 - 38 Carbonation R. = Very good Chloride R. = High GWP = Medium PE-NRe = Low Cost = Very high	NO	The cost is very high
M10sp F 0% C 100% FA 0% SP 1%	0.536	Strength = 50/60 - 37 Carbonation R. = Very good Chloride R. = High GWP = Low PE-NRe = Low Cost = Very high	NO	The cost is very high
M14 F 50% C 100% FA 30%	0.471	Strength = 16/20 - 29 Carbonation R. = Good Chloride R. = High GWP = Low PE-NRe = Very low Cost = Low	NO	The strength is low
M11 F 50% C 100% FA 0%	0.449	Strength = 25/30 - 31 Carbonation R. = Good Chloride R. = Low GWP = Low PE-NRe = Low Cost = Medium	NO	The chloride ion penetration resistance is low
M3sp F 100% C 0% FA 0% SP 1%	0.448	Strength = 30/37 - 33 Carbonation R. = Very good Chloride R. = High GWP = medium PE-NRe = Low Cost = Very high	NO	The cost is very high
M16 F 0% C 100% FA 60%	0.443	Strength = 12/15 - 27 Carbonation R. = Fair Chloride R. = Moderate GWP = Very low PE-NRe = Very low Cost = Very low	NO	The strength is low
M12 F 100% C 100% FA 0%	0.432	Strength = 25/30 – 31 Carbonation R. = Good Chloride R. = Low GWP = Low PE-NRe = Low Cost = Medium	NO	The chloride ion penetration resistance is low
M9sp F 100% C 0% FA 60% SP 1%	0.431	Strength = 16/20 - 29 Carbonation R. = Fair Chloride R. = High GWP = Very low PE-NRe = Very low Cost = Medium	NO	The strength is low
M3 F 100% C 0% FA 0%	0.426	Strength = 25-30 – 31 Carbonation R. = Good Chloride R. = Low GWP = Medium PE-NRe = Low Cost = High	NO	The chloride ion penetration resistance is low
M17 F 50% C 100% FA 60%	0.426	Strength = 12/15 - 27 Carbonation R. = Fair Chloride R. = Moderate GWP = Very low PE-NRe = Very low Cost = Very low	NO	The strength is low
M18 F 100% C 100% FA 60%	0.420	Strength = 12/15 - 27 Carbonation R. = Fair Chloride R. = Moderate GWP = Very low PE-NRe = Very low Cost = Very low	NO	The strength is low
M7 F 0% C 0% FA 60%	0.399	Strength = 12/15 - 27 Carbonation R. = Fair Chloride R. = Moderate GWP = Very low PE-NRe = Very low Cost = Low	NO	The strength is low
M8 F 50% C 0% FA 60%	0.398	Strength = 12/15 - 27 Carbonation R. = Fair Chloride R. = Moderate GWP = Very low PE-NRe = Very low Cost = Low	NO	The strength is low
M9 F 100% C 0% FA 60%	0.381	Strength = 12/15 - 27 Carbonation R. = Fair Chloride R. = Moderate GWP = Very low PE-NRe = Very low Cost = Very low	NO	The strength is low

252 Table 8 - Optimizing concrete mixes for sustainable residential housing in the "GREEN" scenario

Ranked CM	CONCRE***Top*** factor	Threshold	Applicable	Reasons
M10sp F 0% C 100% FA 0% SP 1%	0.343	Strength = 45/55 - 36 Carbonation R. = Very good Chloride R. = Very high GWP = Low PE-NRe = Low Cost = Very high	NO	The cost is very high
M1 F 0% C 0% FA 0%	0.223	Strength = 40/50 - 35 Carbonation R. = Good Chloride R. = Very high GWP = Medium PE-NRe = Low Cost = High	NO	For the green scenario, the GWP is expected to be lower than medium
M3 F 100% C 0% FA 0%	0.211	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Medium PE-NRe = Low Cost = High	NO	For the green scenario, the GWP is expected to be lower than medium
M2 F 50% C 0% FA 0%	0.207	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = High GWP = Medium PE-NRe = Low Cost = High	NO	For the green scenario, the GWP is expected to be lower than medium
M1sp F 0% C 0% FA 0% SP 1%	0.190	Strength = 55/67 - 38 Carbonation R. = Very good Chloride R. = Very high GWP = Medium PE-NRe = Low Cost = Very high	NO	The cost is very high For the green scenario, the GWP is expected to be lower than medium
M3sp F 100% C 0% FA 0% SP 1%	0.168	Strength = 35/45 - 34 Carbonation R. = Very good Chloride R. = High GWP = medium PE-NRe = Low Cost = Very high	NO	The cost is very high For the green scenario, the GWP is expected to be lower than medium

253 Table 9 - Optimizing concrete mixes for high-rise buildings in the "STRENGTH" scenario

Ranked CM	CONCRE***Top*** factor	Threshold	Applicable	Reasons
M10sp F 0% C 100% FA 0% SP 1%	0.542	Strength = 45/55 - 36 Carbonation R. = Very good Chloride R. = Very high GWP = Low PE-NRe = Low Cost = Very high	NO	The cost is very high
M14 F 50% C 100% FA 30%	0.536	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Very high GWP = Low PE-NRe = Very low Cost = Low	NO	The strength is low
M18sp F 100% C 100% FA 60% SP 1%	0.528	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Excellent GWP = Very low PE-NRe = Very low Cost = Low	NO	The strength is low
M15 F 100% C 100% FA 30%	0.508	Strength = 30/37 - 33 Carbonation R. = Fair Chloride R. = Very high GWP = Very low PE-NRe = Low Cost = Low	NO	The strength is low
M5 F 50% C 0% FA 30%	0.502	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Very high GWP = Low PE-NRe = Low Cost = Medium	NO	The strength is low
M9sp F 100% C 0% FA 60% SP 1%	0.500	Strength = 30/37 - 33 Carbonation R. = Fair Chloride R. = Excellent GWP = Very low PE-NRe = Very low Cost = Medium	NO	The strength is low
M7sp F 0% C 0% FA 60% SP 1%	0.492	Strength = 30/37 - 33 Carbonation R. = Fair Chloride R. = Excellent GWP = Very low PE-NRe = Very low Cost = Medium	NO	The strength is low
M16 F 0% C 100% FA 60%	0.473	Strength = 25/30 - 31 Carbonation R. = Fair Chloride R. = Very high GWP = Very low PE-NRe = Very low Cost = Very low	NO	The strength is low
M6	0.466	Strength = 30/37 - 33	NO	The strength is low

F 100% C 0% FA 30%		Carbonation R. = Fair Chloride R. = Very high GWP = Low PE-NRe = Low Cost = Low		
M17 F 50% C 100% FA 60%	0.445	Strength = 20/25 - 30 Carbonation R. = Fair Chloride R. = Very high GWP = Very low PE-NRe = Very low Cost = Very low	NO	The carbonation resistance is poor The strength is low
M18 F 100% C 100% FA 60%	0.441	Strength = 25/30 - 31 Carbonation R. = Fair Chloride R. = Very high GWP = Very low PE-NRe = Very low Cost = Very low	NO	The carbonation resistance is poor The strength is low
M7 F 0% C 0% FA 60%	0.429	Strength = 25/30 - 31 Carbonation R. = Fair Chloride R. = Very high GWP = Very low PE-NRe = Very low Cost = Low	NO	The strength is low
M8 F 50% C 0% FA 60%	0.429	Strength = 25/30 - 31 Carbonation R. = Fair Chloride R. = Very high GWP = Very low PE-NRe = Very low Cost = Low	NO	The strength is low
M9 F 100% C 0% FA 60%	0.413	Strength = 25/30 - 31 Carbonation R. = Fair Chloride R. = Very high GWP = Very low PE-NRe = Very low Cost = Very low	NO	The strength is low
M3sp F 100% C 0% FA 0% SP 1%	0.384	Strength = 35/45 - 34 Carbonation R. = Very good Chloride R. = High GWP = medium PE-NRe = Low Cost = Very high	NO	The cost is very high
M11 F 50% C 100% FA 0%	0.361	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Low PE-NRe = Low Cost = Medium	NO	The strength is low
M12 F 100% C 100% FA 0%	0.341	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Low PE-NRe = Low Cost = Medium	NO	The strength is low
M2 F 50% C 0% FA 0%	0.329	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = High GWP = Medium PE-NRe = Low Cost = High	NO	The strength is low
M3 F 100% C 0% FA 0%	0.320	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Medium PE-NRe = Low Cost = High	NO	The strength is low

Table 10 - Optimizing concrete mixes for residential housing close to the sea in the “SERVICE LIFE” scenario

Ranked CM	CONCRE***Top*** factor	Threshold	Applicable	Reasons
M12sp F 100% C 100% FA 0% SP 1%	0.524	Strength = 35/45 - 34 Carbonation R. = Very good Chloride R. = Moderate GWP = Low PE-NRe = Low Cost = High	NO	The chloride ion’s penetration resistance is moderate
M10 F 0% C 100% FA 0%	0.517	Strength = 35/45 - 34 Carbonation R. = Good Chloride R. = Moderate GWP = Low PE-NRe = Low Cost = Medium	NO	The chloride ion’s penetration resistance is moderate
M11 F 50% C 100% FA 0%	0.433	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Low PE-NRe = Low Cost = Medium	NO	The chloride ion’s penetration resistance is moderate
M12 F 100% C 100% FA 0%	0.408	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Low PE-NRe = Low Cost = Medium	NO	The chloride ion penetration resistance is moderate
M3 F 100% C 0% FA 0%	0.378	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Medium PE-NRe = Low Cost = High	NO	The chloride ion penetration resistance is moderate

Table 11 - Optimizing concrete mixes for economical residential housing in the “COST” scenario

Ranked CM	CONCRE***Top*** factor	Threshold	Applicable	Reasons
M5sp F 50% C 0% FA 30% SP 1%	0.535	Strength = 50/60 - 37 Carbonation R. = Very good Chloride R. = Excellent GWP = Low PE-NRe = Low Cost = High	NO	The cost is high
M10sp F 0% C 100% FA 0% SP 1%	0.425	Strength = 45/55 - 36 Carbonation R. = Very good Chloride R. = Very high GWP = Low PE-NRe = Low Cost = Very high	NO	The cost is very high
M1sp F 0% C 0% FA 0% SP 1%	0.390	Strength = 55/67 - 38 Carbonation R. = Very good Chloride R. = Very high GWP = Medium PE-NRe = Low Cost = Very high	NO	The cost is very high
M1 F 0% C 0% FA 0%	0.385	Strength = 40/50 - 35 Carbonation R. = Good Chloride R. = Very high GWP = Medium PE-NRe = Low Cost = High	NO	The cost is high
M12sp F 100% C 100% FA 0% SP 1%	0.367	Strength = 35/45 - 34 Carbonation R. = Very good Chloride R. = Moderate GWP = Low PE-NRe = Low Cost = High	NO	The cost is high
M3 F 100% C 0% FA 0%	0.341	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = Moderate GWP = Medium PE-NRe = Low Cost = High	NO	The cost is high
M2 F 50% C 0% FA 0%	0.334	Strength = 30/37 - 33 Carbonation R. = Good Chloride R. = High GWP = Medium PE-NRe = Low Cost = High	NO	The cost is high
M3sp F 100% C 0% FA 0% SP 1%	0.295	Strength = 35/45 - 34 Carbonation R. = Very good Chloride R. = High GWP = medium PE-NRe = Low Cost = Very high	NO	The cost is very high

3.7 Final decision (step viii)

The final decision was made based on the CONCRE***Top*** factor (0-1) and threshold values. Both factors rely on the selected scenario and application of the concrete mixes (the mixes are judged according to a points system in each demanded category, not by the position achieved in each one). In the current study, residential housing is considered for most of the cases. However, different scenarios were used to optimize concrete mixes based on specific applications, because residential housing may have to comply with different requirements for EI and applied loads as well as with specific regulations of the country. For example, the regulation of most countries does not yet take into account the EI of concrete 'from cradle to gate". The final decision-making for each scenario is presented in this subchapter.

Generally, for the strength, business as usual and service life scenarios, regardless of the application, the concrete mixes incorporating 50% of fine RCA, 30% of FA and 1% of SP either with ($M14_{sp}$) or without ($M5_{sp}$) 100% coarse RCA are the top options. These two concrete mixes had already been anticipated in step iii (§3.3) as potential OCM (dark grey shade in Table 12). For the cost and green scenarios, the concrete mixes produced with high amounts of FA and RCA (e.g. M16-M18 and $M18_{sp}$) are considered top options (light grey shade in Table 12). Contrary to OCM for strength, business as usual and service life scenarios, the OCM in the cost and green scenarios (M16 and M18sp) were not anticipated in step iii (§3.33.3). Therefore, the OCM may not always be anticipated by comparing the actual characteristics of concrete mixes (step iii - §3.3).

Table 12 - Applicable concrete mixes based on each scenario

Ranking	residential housing far from sea	High-rise building	Residential housing close to the sea	Sustainable residential housing	Economical residential housing
	Business as usual	Strength	Service life	Green	Cost
1	M5sp (F50C0FA50SP)	M5sp (F50C0FA50SP)	M14sp (F50C100FA30SP)	M18 (F100C100FA60)	M18 (F100C100FA60)
2	M14sp (F50C100FA30SP)	M14sp (F50C100FA30SP)	M5sp (F50C0FA50SP)	M17 (F50C100FA60)	M16 (F0C100FA60)
3	M10 (F0C100FA0)	M1sp (F0C0FA0SP)	M18sp (F100C100FA60SP)	M16 (F0C100FA60)	M17 (F50C100FA60)
4	M1 (F0C0FA0)	M13 (F0C100FA30)	M13 (F0C100FA30)	M18sp (F100C100FA60SP)	M13 (F0C100FA30)
5	M13 (F0C100FA30)	M16sp (F0C100FA60SP)	M10sp (F0C100FA0SP)	M16sp (F0C100FA60SP)	M18sp (F100C100FA60SP)
6	M4 (F0C0FA30)	M4 (F0C0FA30)	M14 (F50C100FA30)	M9 (F100C0FA60)	M14 (F50C100FA30)
7	M15 (F100C100FA30)	M10 (F0C100FA0)	M4 (F0C0FA30)	M8 (F50C0FA60)	M15 (F100C100FA30)
8	M5(F50C0FA30)	M1 (F0C0FA0)	M15 (F100C100FA30)	M7 (F0C0FA60)	M14sp (F50C100FA30SP)
9	M16sp (F0C100FA60SP)	M12sp (F100C100FA0SP)	M16 (F0C100FA60)	M13 (F0C100FA30)	M16sp (F0C100FA60SP)
10	M18sp (F100C100FA60SP)	-	M1sp (F0C0FA0SP)	M15 (F100C100FA30)	M9 (F100C0FA60)
11	M12sp (F100C100FA0SP)	-	M5(F50C0FA30)	M14 (F50C100FA30)	M8 (F50C0FA60)
12	M2 (F50C0FA0)	-	M16sp (F0C100FA60SP)	M9sp (F100C0FA60SP)	M7 (F0C0FA60)
13	M7sp (F0C0FA60SP)	-	M17 (F50C100FA60)	M14sp (F50C100FA30SP)	M4 (F0C0FA30)
14	M6 (F100C0FA30)	-	M9sp (F100C0FA60SP)	M7sp (F0C0FA60SP)	M5 (F50C0FA30)
15		-	M18 (F100C100FA60)	M5(F50C0FA30)	M9sp (F100C0FA60SP)
16	-	-	M6 (F100C0FA30)	M6 (F100C0FA30)	M6 (F100C0FA30)
17	-	-	M1 (F0C0FA0)	M4 (F0C0FA30)	M7sp (F0C0FA60SP)
18	-	-	M8 (F50C0FA60)	M5sp (F50C0FA50SP)	M10 (F0C100FA0)
19	-	-	M7 (F0C0FA60)	M10 (F0C100FA0)	M11 (F50C100FA0)
20	-	-	M3sp (F100C0FA0SP)	M12 (F100C100FA0)	M12 (F100C100FA0)
21	-	-	M9 (F100C0FA60)	M11 (F50C100FA0)	M3sp (F100C0FA0SP)
22	-	-	M7sp (F0C0FA60SP)	M12sp (F100C100FA0SP)	-
23	-	-	M2 (F50C0FA0)	-	-

3.7.1 Business as usual scenario

In this scenario, half of the concrete mixes (14 out of 28) are not applicable (Table 13) for "residential housing located far from the sea". This is mainly due to the incorporation of FA, because the hydration process is delayed and requires more time (at least 90 days) to achieve ultimate strength and durability (Kurda et al., 2017). In this scenario, the properties of concrete mixes were considered at 28 days. Thus, some of the non-applicable concrete mixes (M7, M8, M14, M16 and M9sp) did not achieve strength equal to or higher than the threshold value (C20/25 MPa in compressive strength class and 30 GPa in E_{cm}) within this period. The second main reason is cost. For example, the characteristics of $M1_{sp}$, $M3_{sp}$ and $M10_{sp}$ concrete mixes comply with the threshold values set by Kurda et al. (2019a), but their costs are very high. In addition, some other concrete mixes are not applicable (M9, M3, M11 and M12) because their chloride ion penetration resistance is not sufficient at 28 days.

Table 13 - Applicable concrete mixes for residential housing according to the "Business as usual" scenario

NO.	CM	Fine RCA (%)	Coarse RCA (%)	FA (%)	SP (%)	CONCRE***Top*** factor	$f_{ck}/f_{ck,cube}$ - E_{cm}	Cost
1	M5sp	50	0	30	1	0.599	35/45 - 34	High
2	M14sp	50	100	30	1	0.590	30/37 - 33	Medium
3	M10	0	100	0	0	0.536	30/37 - 33	Medium
4	M1	0	0	0	0	0.531	35/45 - 34	High
5	M13	0	100	30	0	0.515	25/30 - 31	Low
6	M4	0	0	30	0	0.494	20/25 - 30	Medium
7	M15	100	100	30	0	0.471	20/25 - 30	Low
8	M5	50	0	30	0	0.469	20/25 - 30	Medium
9	M16sp	0	100	60	1	0.466	25/30 - 31	Medium
10	M18sp	100	100	60	1	0.465	20/25 - 30	Low
11	M12sp	100	100	0	1	0.455	25/30 - 31	High
12	M2	50	0	0	0	0.450	25/30 - 31	High
13	M7sp	0	0	60	1	0.431	25/30 - 31	Medium
14	M6	100	0	30	0	0.428	20/25 - 30	Low

According to the CONCRE***Top*** factor, M5sp is the best-case scenario for the mentioned application. Even though the weight of cost in this scenario is high (45%), the cost of the best-case scenario is high as well. This is mainly related to a good performance in the other concrete characteristics, such as its strength, which is higher than that of the other CM, and its carbonation and chloride ion penetration resistances, which were classified as very good and very high, respectively. Even though the aim of this method is to simplify the selection process of the top CM, it may also indicate other concrete mixes with slightly different characteristics. For example, the difference between the CONCRE***Top*** factor of M13 and M5sp concrete mixes is not huge. Thus, the user can select M13 if the cost of concrete is its main requirement and the strength of both concrete mixes is high enough. However, this method suggests the consideration of the "cost scenario" if the user wants to select the concrete mix with the lowest price.

3.7.2 Strength

It is well-known that high-strength concrete is required for making high-rise buildings. Therefore, the strength scenario was considered for this application. In this method, a strength class of 35/45 - 34 ($f_{ck}/f_{ck,cube}$ - E_{cm}) was considered as the acceptable minimum. As shown in Table 14, about one-third of the concrete mixes are not applicable for this use. This is mainly due to their low strength, even at longer ages. However, the concrete mix with the highest strength (M1sp) is not considered the best option. In fact, the cost of concrete also influences this decision (according to the weight specified for each category in the study of Kurda et al. (2019a) and the cost of M1sp is very high. In addition, for this application, a high incorporation ratio of FA in concrete without using SP is not applicable due to its low strength.

Table 14 - Applicable concrete mixes for high-rise buildings according to the “Strength” scenario

NO.	CM	Fine RCA (%)	Coarse RCA (%)	FA (%)	SP (%)	CONCRE*Top* factor	Strength	Cost
1	M5sp	50	0	30	1	0.658	50/60 - 37	High
2	M14sp	50	100	30	1	0.656	45/55 - 36	Medium
3	M1sp	0	0	0	1	0.590	55/67 - 38	Very high
4	M13	0	100	30	0	0.585	35/45 - 34	Low
5	M16sp	0	100	60	1	0.563	35/45 - 34	Medium
6	M4	0	0	30	0	0.532	35/45 - 34	Medium
7	M10	0	100	0	0	0.457	35/45 - 34	Medium
8	M1	0	0	0	0	0.432	40/50 - 35	High
9	M12sp	100	100	0	1	0.400	35/45 - 34	High

3.7.3 Service life

Generally, carbonation and chloride ion penetration resistances are the two main factors that need to be considered in the service life performance of concrete. However, the weight of each characteristic may not necessarily be the same, e.g. the carbonation resistance of concrete for a residential housing close to the sea may not necessarily be high, while the resistance to chloride ion penetration should be high for the same application. Similarly to the “business as usual” and “strength scenarios”, the top best concrete mixes ($M14_{sp}$, $M5_{sp}$) are those made with both FA and RCA, and the lowest ranking concrete mixes are those produced with RCA only (Table 15).

Table 15 - Applicable concrete mixes for residential housing close to the sea according to the “Service life” scenario

NO.	CM	Fine RCA (%)	Coarse RCA (%)	FA (%)	SP (%)	CONCRE***Top*** factor	Strength	Carbonation resistance	Chloride resistance	Cost
1	M14sp	50	100	30	1	0.715	45/55 - 36	Fair	Excellent	Medium
2	M5sp	50	0	30	1	0.693	50/60 - 37	Very good	Excellent	High
3	M18sp	100	100	60	1	0.628	30/37 - 33	Fair	Excellent	Low
4	M13	0	100	30	0	0.598	35/45 - 34	Fair	Very high	Low
5	M10sp	0	100	0	1	0.590	45/55 - 36	Very good	Very high	Very low
6	M14	50	100	30	0	0.584	30/37 - 33	Fair	Very high	Low
7	M4	0	0	30	0	0.560	35/45 - 34	Fair	Very high	Medium
8	M15	100	100	30	0	0.556	30/37 - 33	Fair	Very high	Low
9	M16	0	100	60	0	0.554	25/30 - 31	Fair	Very high	Very low
10	M1sp	0	0	0	1	0.550	55/67 - 38	Very good	Very high	Very high
11	M5	50	0	30	0	0.547	30/37 - 33	Fair	Very high	Medium
12	M16sp	0	100	60	1	0.546	35/45 - 34	Fair	Excellent	Medium
13	M17	50	100	50	0	0.535	20/25 - 30	Fair	Very high	Very low
14	M9sp	100	0	60	1	0.530	30/37 - 33	Fair	Excellent	Medium
15	M18	100	100	60	0	0.528	25/30 - 31	Fair	Very high	Medium
16	M6	100	0	30	0	0.495	30/37 - 33	Fair	Very high	Low
17	M1	0	0	0	0	0.482	40/50 - 35	Good	Very high	High
18	M8	50	0	60	0	0.481	25/30 - 31	Fair	Very high	Low
19	M7	0	0	60	0	0.479	25/30 - 31	Fair	Very high	Low
20	M3sp	100	0	0	1	0.477	35/45 - 34	Fair	High	Very low
21	M9	100	0	60	0	0.466	25/30 - 31	Fair	Very high	Very low
22	M7sp	0	0	60	1	0.465	30/37 - 33	Fair	Excellent	Medium
23	M2	50	0	0	0	0.414	30/37 - 33	Good	High	High

3.7.4 Green

The best option to build a sustainable residential housing is by using a “green scenario”. According to the CONCRE***Top*** factor, the mix with 60% FA and 100% of coarse and fine RCA (M18) is the best concrete mix to build this kind of residential housing. Along with the low EI of this concrete mix, the cost to obtain it is also very low. In addition, the top concrete mixes (e.g., M17, M16 and M18$_{sp}$) are those made with both FA and RCA, and the lowest ranking concrete mixes are those produced with RCA only but without FA. Thus, it is advisable to use both RCA and FA to obtain a sustainable concrete mix (Table 16).

3.7.5 Cost

In the construction sector, namely to build residential housing, following the “business as usual” scenario, the cost scenario can be considered as the 2nd most common scenario. In this scenario, the use of SP is not applicable unless high volumes of RCA or FA are incorporated in the concrete mix (Table 17).

Table 16 - Applicable concrete mixes for sustainable residential housing according to the “Green” scenario

NO.	CM	Fine RCA (%)	Coarse RCA (%)	FA (%)	SP (%)	CONCRE*Top* factor	Strength	GWP	PE-NRe	Cost
1	M18	100	100	60	0	0.828	25/30 - 31	Very low	Very low	Very low
2	M17	50	100	60	0	0.821	20/25 - 30	Very low	Very low	Very low
3	M16	0	100	60	0	0.819	25/30 - 31	Very low	Very low	Very low
4	M18sp	100	100	60	1	0.799	30/37 - 33	Very low	Very low	Low
5	M16sp	0	100	60	1	0.770	35/45 - 34	Very low	Very low	Medium
6	M9	100	0	60	0	0.669	25/30 - 31	Very low	Very low	Very low
7	M8	50	0	60	0	0.667	25/30 - 31	Very low	Very low	Low
8	M7	0	0	60	0	0.651	25/30 - 31	Very low	Very low	Low
9	M13	0	100	30	0	0.629	35/45 - 34	Low	Very low	Low
10	M15	100	100	30	0	0.629	30/37 - 33	Very low	Low	Low
11	M14	50	100	30	0	0.629	30/37 - 33	Low	Very low	Low
12	M9sp	100	0	60	1	0.626	30/37 - 33	Very low	Very low	Medium
13	M14sp	50	100	30	1	0.609	45/55 - 36	Very low	Very low	Medium
14	M7sp	0	0	60	1	0.587	30/37 - 33	Very low	Very low	Medium
15	M5	50	0	30	0	0.472	30/37 - 33	Low	Low	Medium
16	M6	100	0	30	0	0.469	30/37 - 33	Low	Low	Low
17	M4	0	0	30	0	0.467	35/45 - 34	Low	Low	Medium
18	M5sp	50	0	30	1	0.452	50/60 - 37	Low	Low	High
19	M10	0	100	0	0	0.379	35/45 - 34	Low	Low	Medium
20	M12	100	100	0	0	0.361	30/37 - 33	Low	Low	Medium
21	M11	50	100	0	0	0.359	30/37 - 33	Low	Low	Medium
22	M12sp	100	100	0	1	0.330	35/45 - 34	Low	Low	High

Similarly to the green scenario, M18 (100% fine and coarse RCA, and 60% FA) is the best option to build economical residential housing. However, according to this method, the highest CONCRE***Top*** factor value (best CM) does not have to correspond to the concrete mixes with the lowest cost, because in the cost scenario the strength of concrete also affects the final decision to select the OCM. In other words, the structural elements with higher strength concrete mixes need a smaller cross-section than those with lower strength CM, and this significantly influences the total volume of the concrete required to build the same residential housing, and consequently the total cost.

Table 17 - Applicable concrete mixes for economical residential housing according to the "COST" scenario

NO.	CM	Fine RCA (%)	Coarse (%)	RCA FA (%)	SP (%)	CONCRE*Top* factor	Strength	Cost
1	M18	100	100	60	0	0.635	25/30 - 31	Very low
2	M16	0	100	60	0	0.629	25/30 - 31	Very low
3	M17	50	100	60	0	0.625	25/30 - 31	Very low
4	M13	0	100	30	0	0.619	35/45 - 34	Low
5	M18sp	100	100	60	1	0.607	30/37 - 33	Low
6	M14	50	100	30	0	0.603	30/37 - 33	Low
7	M15	100	100	30	0	0.597	30/37 - 33	Low
8	M14sp	50	100	30	1	0.595	45/55 - 36	Medium
9	M16sp	0	100	60	1	0.591	35/45 - 34	Medium
10	M9	100	0	60	0	0.558	25/30 - 31	Very low
11	M8	50	0	60	0	0.556	25/30 - 31	Low
12	M7	0	0	60	0	0.540	25/30 - 31	Low
13	M4	0	0	30	0	0.529	35/45 - 34	Medium
14	M5	50	0	30	0	0.524	30/37 - 33	Medium
15	M9sp	100	0	60	1	0.523	30/37 - 33	Medium
16	M6	100	0	30	0	0.514	30/37 - 33	Low
17	M7sp	0	0	60	1	0.482	30/37 - 33	Medium
18	M10	0	100	0	0	0.459	35/45 - 34	Medium
19	M11	50	100	0	0	0.410	30/37 - 33	Medium
20	M12	100	100	0	0	0.410	30/37 - 33	Medium

4 Conclusions

This study is an example of CONCRE***Top***'s application and also contributes to its validation. This work proposes an innovative methodology for the optimization of concrete mixes with different applications and scenarios. The novelty of this methodology is its wide-range in terms of types of concrete, considering multiple characteristics. In fact, there is not a specific method to optimize CM. CONCRE***Top*** is straightforward in its application, which does not require excessive time and resources, and is focused on the final output, where the selection of the OCM can be directly used by the user, avoiding therefore lengthy inventory analysis and modifications. In this study, the scope of CONCRE***Top*** was limited to optimizing the technical performance, cost and EI of 28 concrete mixes with high incorporation levels of FA and RCA, without or with SP. The result show that this methodology can be applied to any concrete mixes (traditional and non-traditional) and different applications. The following points can be highlighted for the selected applications and scenario.

- The use of CONCRE***Top*** in the selected applications shows that the OCM may not be easily considered by simply comparing the actual characteristics of CM. In fact, for each application, it mainly depends on the CONCRE***Top*** factors and threshold values. For example, in the cost and green scenarios, the concrete mixes made with high incorporation levels of FA and RCA (e.g. M16-M18 and $M18_{sp}$) are not anticipated to be an OCM according to their actual characteristics, but their CONCRE***Top*** factors were high and complied with the threshold values. Therefore, they were considered as OCM.

- The OCM may not necessarily obtain the highest weight in all concrete characteristics. In fact, the OCM are determined by the joint performance (weight) in all the characteristics of the CM. This means the performance is judged according to weights for each characteristic, not by one characteristic only. For example, in the strength (high-rise buildings) scenario, the mix with the highest compressive strength was not considered the best option. Furthermore, the concrete mixes with the highest CONCRE***Top*** factor may not always be the OCM, namely when one or more than one of its characteristics do not comply with the threshold values.

- Generally, the final decision depends on the selected scenario and application of the CM, e.g. for the strength (high-rise buildings), business as usual (residential housing far from the sea) and service life (residential housing close to the sea) scenarios, of the 28 concrete mixes (RCA 0-100%; FA 0-60%; SP 0-1%), the one incorporating 50% of fine RCA, 30% of FA and 1% of SP either with ($M14_{sp}$) or without ($M5_{sp}$) 100% coarse RCA are in the top options. For the cost (economical residential housing) and green (sustainable residential housing) scenarios, the concrete mixes made with high incorporation levels of FA and RCA (e.g. M16-M18 and $M18_{sp}$) are considered top options.
- Even though the aim of this method is to simplify the selection process of the top CM, it may also indicate other concrete mixes with slightly different characteristics. For example, in the strength scenario, if the difference between the CONCRE***Top*** factors of two concrete mixes is not significant, the user can select the mix that has a slightly lower CONCRE***Top*** factor if cost is its main requirement and all technical requirements are fulfilled by the alternatives.

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