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Optimizing the economic, environmental and technical performance of concrete mixes with fly ash and recycled concrete aggregates

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Abstract. This study answers an important question that may arise when selecting a sustainable concrete, namely “concrete mixes containing low cement and recycled aggregates are a sustainable solution?” To answer this question, this study shows how to optimize concrete mixes in terms of technical performance, and economic and environmental life cycle. Firstly, the weight to be considered for each of these dimensions of performance depends on the concrete application (e.g. residential house and high-rise building) and on the consumer’s requirements (e.g. business as usual, green, strength, service life and cost scenarios). In this study, concrete mixes containing recycled concrete aggregates (RCA) and/or fly ash (FA) are optimized to be used in sustainable residential houses. For that purpose, the **CONCRETop** methodology (developed by the same authors of this study) was applied to these concrete mixes by considering a “green scenario”. The results show that, for sustainable residential houses, the concrete mixes made with high incorporation ratios of FA and RCA are considered the best option.

1. Introduction

Concrete has a serious influence on environmental impacts (EI) due to the fact that it is the most consumed product by Man after water. Thus, many alternative ways were suggested to decrease its influence on EI, specifically by using cementitious [1-7] and recycled materials [8-20]. For that purpose, there were many attempts to study the effect of non-conventional materials on the cost, quality (e.g. durability and mechanical characteristics) and EI (energy consumption and greenhouse gas emissions) of concrete. Since most of the studies focused on only one of the mentioned dimensions of performance (quality, cost and EI), and there is no direct relationship between them, a critical gap occurs concerning the assessment of sustainable concrete. Even though, there are many alternative materials which use in concrete is a sustainable solution because their EI are lower than that of the conventional materials. However, the advantage of these non-traditional materials may not be obvious when the service life of the concrete mixes made with them compares with that of conventional concrete.

To analyse these issues, this study optimized concrete mixes containing various incorporation ratios of fly ash (FA) and recycled aggregates (RA), with and without superplasticizer (SP). But it is not easy to compare the performance of concrete mixes considering simultaneously several dimensions of performance. Thus, the authors of this study had already proposed a novel method (**CONCRETop** - A multi-criteria decision method for concrete optimization - [21]) to optimize conventional and non-



conventional concrete mixes in the mentioned dimensions. For that purpose, the *CONCRETop* methodology was applied to these concrete mixes by considering a “green scenario”. This study is an example of *CONCRETop*'s application and also contributes to its validation.

2. Materials and methods

This study followed the steps that are described in the *CONCRETop* method [21] to optimize concrete mixes. As mentioned before, the concrete mixes can be optimized only when their quality, EI and cost are known. It is known that the environmental and cost life cycle assessment data of different concrete mixes cannot be directly compared. Accordingly, the *CONCRETop* method used a non-parametric linear technique to optimize the concrete mixes. In addition, the aim of the *CONCRETop* method is to simply compare the options without any complex analyses (e.g. Holomorphic function, disk algebra and power series) in order to be used by any Engineer in the construction industry. According to the *CONCRETop* method, seven actions are required to reach a final decision (Figure 1).

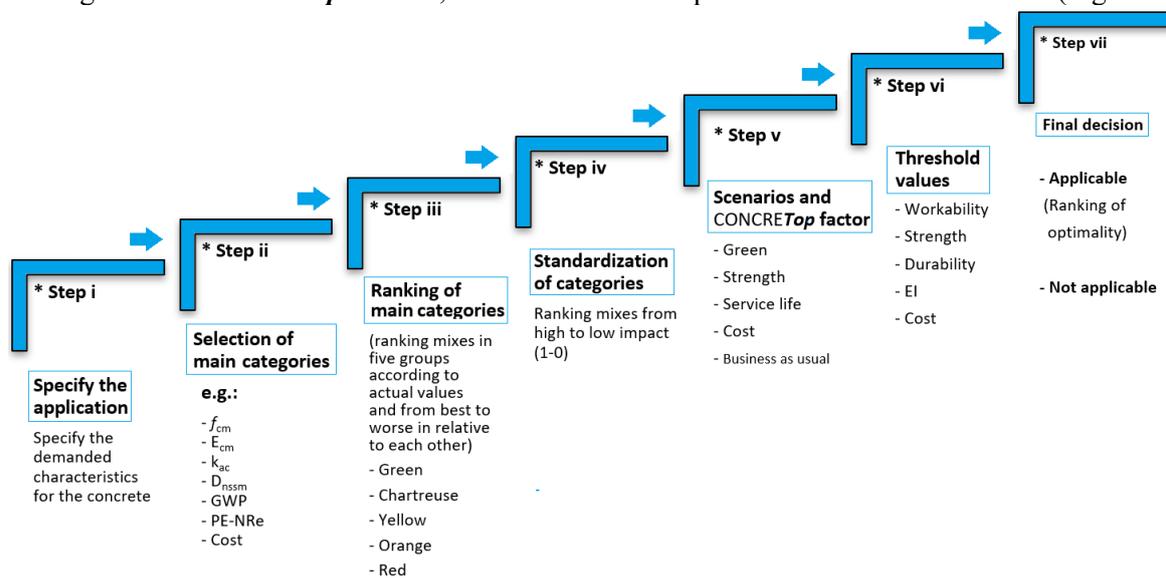


Figure 1 - Profile of the *CONCRETop*. Each step is described in study [21]

Cement and FA used as binders were type “CEM I 42.5 R” and “F”, respectively. The fine and coarse RA are made from the same source concrete without any contamination (100% concrete). The fine and coarse natural aggregates (NA) are “natural silica sand” and “crushed limestone”, respectively. In this study, 20 concrete mixes (Table 1) are considered to be optimized. They were made with various incorporation ratio of FA (0%, 30% and 60%), fine RA (0%, 50 and 100%), coarse RA (0% and 100%) and SP (0% and 1%). All the information related to the characteristics of the materials (e.g. size of aggregates, density, and water absorption) and mix composition (e.g. mixing procedure, quantity of materials) is described in another study by the same authors [22].

To consider the requirements needed to optimize concrete mixes, the following standards were considered to determine the compressive strength [23], modulus of elasticity [24], carbonation [25], chloride ion penetration [26, 27], cost, and global warming potential and non-renewable primary energy consumption (based on Life Cycle Assessment (LCA) methodology [28, 29]) of the concrete mixes. Regarding LCA, the EI of the concrete mixes were found by considering the most probable case scenario in the centre of Portugal (Lisbon region). Further details regarding the mentioned characteristics (e.g. curing procedure, size of samples, number of samples and case scenario) are described in previous studies of the same authors [5, 7, 30, 31].

3. Application of CONCRE Top to the concrete mixes

3.1 Specification of the application (step i)

As detailed in the CONCRE Top methodology, the optimization process of concrete mainly depends on its application. In this study, the concrete mixes are optimized to be used in a “sustainable residential houses”. According to this methodology, “sustainable residential houses” will be categorized according to a “green” scenario. Thus, the threshold values that are specified for the green scenario were applied to the concrete mixes.

Table 1 - Mixes composition

Mixes ^a	Fine RA (%)	Coarse RA (%)	FA (%)
M1; M1-SP	0	0	0
M2; M2-SP	100	0	0
M3; M3-SP	50	0	30
M4; M4-SP	0	0	60
M5; M5-SP	100	0	60
M6; M6-SP	0	100	0
M7; M7-SP	100	100	0
M8; M8-SP	50	100	30
M9; M9-SP	0	100	60
M10; M10-SP	100	100	60

^a M and M-SP are concrete mixes without and with SP (1% of binder’s weight)

3.2 Selection of the main categories (step ii)

There are many characteristics that can be considered to optimize concrete. The CONCRE Top method specifies the most relevant ones for this purpose, but unlimited characteristics can be considered using this method. According to this method, the following characteristics are relevant for the green scenario: workability, compressive strength (f_{cm}), modulus of elasticity (E_{cm}), carbonation resistance, chloride ion penetration resistance (D_{nssm}), global warming potential (GWP) and non-renewable energy consumption (PE-NRe).

3.3 Ranking of the main categories (step iii)

Before optimizing the concrete mixes based on the next steps (§3.4-§3.5), namely by considering the weight of each category, mathematical rules and threshold values, the characteristics of the concrete mixes were compared to each other in order to provide a general idea about their performance. However, the aim of the CONCRE Top method is to find an optimal mixes instead of the best one in each category. According to this methodology, the results of the concrete mixes were compared (Table 2), namely by two main colours (green for the best performance and red for the worst performance). According to this step, mixes M3, M3-SP, M4-SP, M6-SP and M8-SP were identified as optimal for “sustainable residential houses”, because most of their characteristics are not in the red category.

3.4 Standardization of categories (step iv)

The characteristic values of concrete mixes are standardized based on step iv from Kurda *et al.* [21]. It is known that the results of different properties cannot be compared if their measuring unit are not the same. Therefore, the actual values of all characteristic were standardized (normalised or homogenised) from 0 to 1. Then, the mixes were ranked according to the standardized values from the best to the worst performance (Table 3).

3.5 Scenarios and CONCRE Top factor (step v)

This step is one of the most important of the optimization process because the mixes were ranked based on the CONCRE Top factor. This factor can be determined by the equation proposed in this method [21]. In addition, for the selected scenario (green), the weight of each category (characteristic

of concrete) for the CONCRE**Top** factor is defined in the same method according with their order of importance. For the selected application and scenario, the weight of the strength, durability, LCA and cost are 10%, 20%, 50% and 20%, respectively (based on 20 years of experience of one of the authors of this manuscript as a structural designer.). According to the CONCRE**Top** method, the weights can be changed, depending on the client’s perspective. However, this method was prepared for engineers with basic knowledge regarding the construction sector in order to choose the weights. But this method also include threshold values to overcome this issue. Even if the weights are not always considered properly, the threshold values will not permit inadequate choices. Figure 2 presents the result of the process of optimization of the concrete mixes based on green scenario ranked by their CONCRE**Top** factor (1-0) without considering threshold values.

Table 2 - Ranking of concrete mixes according to their performance

Concrete mixes	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	7.3	55.8	61.3	43.8	47	12.6	7.9	11.3	361.6	1949.5	79.9
M1-SP	8.5	73.5	83	51.4	55.7	6.4	3.9	1.6	364	1983.2	90.1
M2	8.1	45	51.5	34.7	39	16.2	9.8	26.9	360	1936.2	76.7
M2-SP	8.8	54.1	63.7	39.9	42.6	9.4	5.5	7.8	362.5	1970.8	86.7
M3	8.3	36.4	57.2	38.3	46.3	8.9	3	37.7	267.9	1572.2	71
M3-SP	8.9	60.4	79	43.9	50.2	4.2	1.0	4.2	270.3	1605.6	81.1
M4	7.2	24	42.2	38	46.1	11.2	3.1	61.58	175.9	1209.7	65.3
M4-SP	8.1	42.4	58	40.7	47.7	5.4	1.1	59.84	178.7	1248.1	75.5
M5	8.5	21.5	40	32.3	41.4	13.2	3.3	66.4	174.2	1194.5	62.2
M5-SP	8	37.1	57	34.4	42	6.6	1.3	51.83	176.6	1228.5	72.1
M6	7.6	51.9	59.2	37.1	41.4	14	8.5	15.35	331.1	1528.6	74.6
M6-SP	8.8	63	73	43.5	47.7	7.6	4.6	1.5	331.8	1538.2	84.5
M7	8.1	42	50.2	28	31.4	18.1	10.6	30.3	330.3	1525.4	71.6
M7-SP	8.9	49	60.6	33.9	35.8	10.6	6.1	9	331	1534.9	81.2
M8	8.8	33	56.6	32.5	40	9.3	3.2	42.3	237.6	1153.9	65.8
M8-SP	8.7	53.8	74	38.3	44	4.6	1.1	12.2	238.3	1163.4	75.5
M9	8.6	23	41	33	41.1	11.9	3.2	59.8	145	783.1	59.9
M9-SP	8.8	38	59	38.3	43.6	5.9	1.2	57.1	145.7	792.6	69.8
M10	7.3	21	38	26.9	35.3	14.2	3.6	66.3	144.2	779.1	57
M10-SP	8.9	32.3	54	30.1	35.5	7.3	1.4	44	144.8	788.7	66.6

Table 3 - Ranking and standardization of the concrete mixes

f_{cm} (28 days)	f_{cm} (365 days)	E_{cm} (28 days)	E_{cm} (365 days)	D_{nssm} (28 days)	D_{nssm} (365 days)	Carbonation	GWP	PE-NRe	Cost										
M1-SP	1.00	M1-SP	1.00	M1-SP	1.00	M3-SP	1.00	M6-SP	1.00	M10	1.00	M10	1.00						
M6-SP	0.80	M3-SP	0.91	M3-SP	0.69	M3-SP	0.77	M8-SP	0.97	M4-SP	0.99	M1-SP	1.00	M9	1.00	M9	0.91		
M3-SP	0.75	M8-SP	0.80	M1	0.69	M4-SP	0.67	M4-SP	0.91	M8-SP	0.99	M3-SP	0.96	M9	1.00	M10-SP	0.99	M5	0.84
M1	0.66	M6-SP	0.78	M6-SP	0.68	M6-SP	0.67	M9-SP	0.88	M9-SP	0.98	M2-SP	0.90	M9-SP	0.99	M9-SP	0.99	M4	0.75
M2-SP	0.63	M2-SP	0.57	M4-SP	0.56	M1	0.64	M1-SP	0.84	M5-SP	0.97	M7-SP	0.88	M5	0.86	M8	0.69	M8	0.73
M8-SP	0.62	M1	0.52	M2-SP	0.53	M3	0.61	M5-SP	0.83	M10-SP	0.96	M1	0.85	M4	0.86	M8-SP	0.68	M10-SP	0.71
M6	0.59	M7-SP	0.50	M3	0.47	M4	0.60	M10-SP	0.78	M3	0.79	M8-SP	0.84	M5-SP	0.85	M5	0.66	M9-SP	0.61
M7-SP	0.53	M6	0.47	M8-SP	0.47	M8-SP	0.52	M6-SP	0.76	M4	0.78	M6	0.79	M4-SP	0.84	M4	0.64	M3	0.58
M2	0.46	M9-SP	0.47	M9-SP	0.47	M9-SP	0.50	M3	0.66	M8	0.77	M2	0.61	M8	0.58	M5-SP	0.63	M7	0.56
M4-SP	0.41	M4-SP	0.44	M4	0.45	M2-SP	0.46	M8	0.63	M9	0.77	M7	0.56	M8-SP	0.57	M4-SP	0.61	M5-SP	0.54
M7	0.40	M3	0.43	M6	0.42	M5-SP	0.44	M2-SP	0.63	M5	0.76	M3	0.44	M3	0.44	M7	0.38	M6	0.47
M9-SP	0.32	M5-SP	0.42	M2	0.32	M5	0.41	M7-SP	0.54	M10	0.73	M8	0.37	M3-SP	0.43	M6	0.38	M4-SP	0.44
M5-SP	0.31	M8	0.41	M5-SP	0.31	M6	0.41	M4	0.50	M1-SP	0.70	M10-SP	0.35	M7	0.15	M7-SP	0.37	M8-SP	0.44
M3	0.29	M10-SP	0.36	M7-SP	0.29	M9	0.40	M9	0.45	M6-SP	0.63	M5-SP	0.22	M7-SP	0.15	M6-SP	0.37	M2	0.40
M8	0.23	M2	0.30	M9	0.25	M8	0.35	M1	0.40	M2-SP	0.53	M9-SP	0.14	M6	0.15	M3	0.34	M1	0.31
M10-SP	0.22	M7	0.27	M8	0.23	M2	0.31	M5	0.35	M7-SP	0.47	M9	0.10	M6-SP	0.15	M3-SP	0.31	M3-SP	0.27
M4	0.06	M4	0.09	M5	0.22	M7-SP	0.18	M6	0.29	M1	0.28	M4-SP	0.10	M2	0.02	M2	0.04	M7-SP	0.27
M9	0.04	M9	0.07	M10-SP	0.13	M10-SP	0.17	M10	0.28	M6	0.22	M4	0.07	M1	0.01	M1	0.03	M6-SP	0.17
M5	0.01	M5	0.04	M7	0.04	M10	0.16	M2	0.14	M2	0.08	M10	0.00	M2-SP	0.01	M2-SP	0.01	M2-SP	0.10
M10	0.00	M10	0.00	M10	0.00	M7	0.00	M7	0.00	M7	0.00	M5	0.00	M1-SP	0.00	M1-SP	0.00	M1-SP	0.00

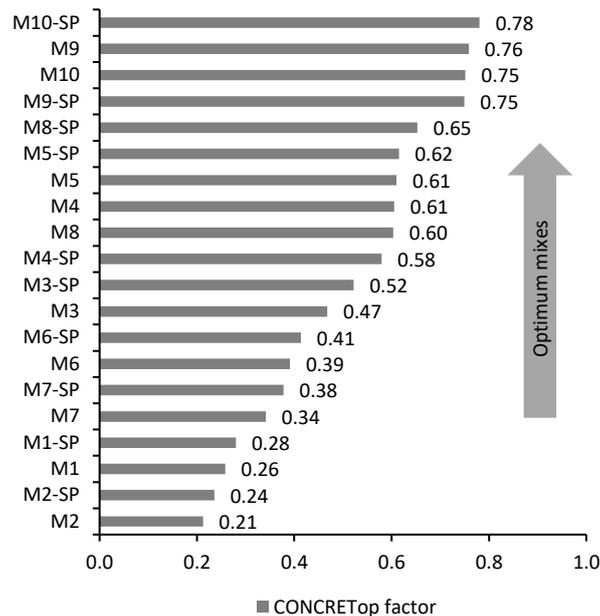


Figure 2 -Optimization of the concrete mixes according to green scenarios without considering threshold values

3.6 Threshold values (step vi)

As mentioned before, the considered weight may not be reliable or correct. Therefore, this step works as another sort of screen to optimize the concrete mixes. The boundaries (threshold values) for all the selected parameters (f_{cm} , E_{cm} , carbonation, D_{nssm} , GWP and PE-NRE) for this step are identified in the study of Kurda *et al.* [21]. According to this method, the threshold value depends on the case study. Thus, in this step, green scenario and its threshold value were chosen out of all scenarios (business as usual, strength, cost and service life) due to the fact that the concrete mixes are optimized for sustainable residential houses. Thus, the concrete mixes were ordered based on the values shown in Figure 2, and then the results were compared with the threshold values set by the mentioned study (Table 4). The concrete mixes that comply with the threshold values are not presented in Table 4. The results show that, along with the fact that the values of the CONCRETop factor of the traditional concrete (M1 and M1-SP) and of mixes containing 100% of fine RA (M2 and M2-SP), with and without SP, are relatively low, their characteristics also do not comply with the boundaries given by CONCRETop method.

3.7 Final decision (step viii)

One of the advantages of the CONCRETop method is that the consumer can easily choose the optimal mix for the selected application. According to the optimization process, mix M10-SP is the optimal one (highest CONCRETop factor) and the worst one is mix M7 (lowest CONCRETop factor). Based on the mentioned factor, all the mixes made with 100% coarse RA and 60% FA (M10-SP, M9, M10 and M9-SP) can be considered as optimal choices for sustainable residential houses (their CONCRETop factor is relatively similar). Thus, it is advisable to use high volume of coarse RA and FA to build sustainable residential houses. Furthermore, the method shows that the EI of the fine RA concrete made with ordinary Portland cement (OPC; M7 and M7-SP) is lower than that of conventional concrete, but it is still considered one of the worst choices because it significantly affects the service life of concrete.

The above conclusions show that consumers need to consider other dimensions of performance (e.g. quality and cost of concrete) to select the optimal/sustainable concrete, even if they only demand EI's minimization. In addition, the optimal mixes cannot be easily anticipated by simply looking at the individual results in each dimension (§3.3). Furthermore, in some cases, the high-strength concrete mixes are not considered as an optimum [21] solution due to their cost (their cost are very high) or EI (due to high cement content which is the major contributor to the high EI values of concrete).

Table 4 - Optimizing concrete mixes for sustainable residential house in the "GREEN" scenario

Ranked mixes	CONCRETop factor	Threshold	Applicable [21]	Reasons
M6-SP F 0% C 100% FA 0% SP 1%	0.41	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-SP	0.28	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.
M1	0.26	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.
M2-SP	0.24	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.
M2	0.21	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.

Table 5 - Applicable concrete mixes for the sustainable residential house according to the "Green" scenario

Mixes	M10-SP	M9	M10	M9-SP	M8-SP	M5-SP	M5	M4	M8	M4-SP	M3-SP	M3	M6	M7-SP	M7
Fine RA (%)	100	0	100	0	50	100	100	0	50	0	50	50	0	100	100
Coarse RA (%)	100	100	100	100	100	0	0	0	100	0	0	0	100	100	100
FA (%)	60	60	60	60	30	60	60	60	30	60	30	30	0	0	0
SP (%)	1	0	0	1	1	1	0	0	0	1	1	0	0	1	0
CONCRETop factor	0.78	0.76	0.75	0.75	0.65	0.62	0.61	0.61	0.6	0.58	0.52	0.47	0.39	0.38	0.34

4. Conclusions

The results of this study show that the optimum concrete mixes may not be easily chosen by comparing the performance of concrete in each dimension (e.g. quality, cost and EI). In practical terms, for each selected application, it relies on the CONCRETop factor and threshold values. In other words, the weight of each characteristic depends on the specific concrete application. For example, mixes produced with high incorporation ratios of FA and RCA (e.g. M9 and M10 with and without SP) are not anticipated to be an optimal choice according to their individual characteristics, but their characteristics comply with the threshold values and their CONCRETop factors are the highest. In addition, the optimal mix (e.g. for sustainable house) may not necessarily be the one with the highest result in the demanded characteristic (e.g. EI). In practical terms, it is chosen by the combined performance in all the characteristics. Broadly speaking, the mixes are judged based on their performance on all characteristics, not in just one characteristic (dimension).

Finally, this study is an example of CONCRETop application and shows that concrete cannot be optimized without knowing its application and the consumer's demand. Therefore, the outcome may be different for other approaches or assumed scenarios.

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