- Technical Paper -

BEHAVIOR-BASED INDICATOR REDUCTION TECHNIQUE FOR EVALUATING THE SUSTAINABILITY OF CONCRETE

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ABSTRACT
Concrete sustainability evaluation needs less but valuable indicators. A technique using the coefficient of variation to eliminate progressively indicators from an exhaustive set to form reduced sets of indicators is presented. The effect of the reduction was evaluated using analytic hierarchy process, suggesting that the ranking of alternatives is less sensitive to the omission of trivial indicators, thereby, leading to the identification of the relatively most sustainable concrete mix. This technique, therefore, has significant applications in indicator selection for sustainable concrete analysis.
Keywords: indicators, indicator selection, sustainable concrete, analytic hierarchy process

1. INTRODUCTION

Concrete sustainability became the focus of many researchers and industry practitioners because of the objectionable impacts of concrete – the second most consumed material worldwide. The common convention to picture concrete sustainability is through indicators – tools to measure significant performances, associated environmental emissions, and economic values. Despite the presence of indicators in literature, indicator selection is still debated in the sector, suggesting that consensus on sustainable concrete is yet to be reached.

In performing indicator-based concrete sustainability, a difficulty arises in selecting a set of appropriate indicators. The trend in indicator selection relies on an arbitrary identification of suitable indicators based on expert's opinion, or on a participatory judgment by stakeholders. The idea is to come up with indicators holistic enough to represent the sustainability of concrete material since it is an accepted good practice to not simply follow a tick box mentality on the use of assessment tools, but to understand the factors and take a whole-life view of sustainability [1]. This, however, may result in an unreasonably high number of indicators that overwhelm and complicate the analysis, making interpretability unmanageable.

Contrary to employing a multitude of indicators, evaluation should not just gather a large set of indicators but, preferably, analyze the ones that are fundamental in essence and likely to produce the most accurate information [2]. The analysis, accordingly, should accentuate those indicators that better reflect the sustainability of concrete material. Hak et al. add, selecting appropriate indicators from existing sets should be done within a conceptual framework focused on the 'indicator-indicated fact' [3]. The challenge, therefore, rests not only in selecting indicators, but extends on systematically analyzing them to put more value on indicators that resonate significant behaviors relative to others across alternatives.

This paper contributes to the debate by presenting a rational methodology to select the 'indicative-indicators' from the exhaustive set of indicators for concrete sustainability analysis. The technique is grounded on the analysis of the relative variability of indicators to distinguish those that are desirable to be used as criteria for comparison, consequently reducing the set. The effect of reducing indicators on the ranking and on the selection of a more sustainable concrete alternative using this technique is demonstrated.

2. METHODS

The framework in Fig. 1, is designed to comparatively analyze the indicators and to compare the different concrete mix alternatives. The alternatives are concrete mixes potentially more sustainable than a reference mix. The framework helps distinguish the indicators that exhibit higher relative variation, instrumental in reducing the number of indicators for concrete sustainability analysis.

2.1 Sample Data

The data in the sample calculation was from the previous work of Henry et al. [4], where the effect of the various amounts of low-grade recycled aggregates (0%, 50%, and 100% RA replacement ratio) and mineral admixtures (fly ash and blast slag) was investigated at varying water-binder (W/B) ratios (0.3, 0.375, and 0.45). Table 1 shows the mix proportions of the alternatives with the same series names as the reference. The data on blast slag was excluded to reduce the number of varying factors to only the amount of recycled aggregate and the water-binder ratio. In addition, since the fly ash content was constant

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in all alternatives, its contribution to sustainability evaluation was treated as part of the total amount of recycled materials.

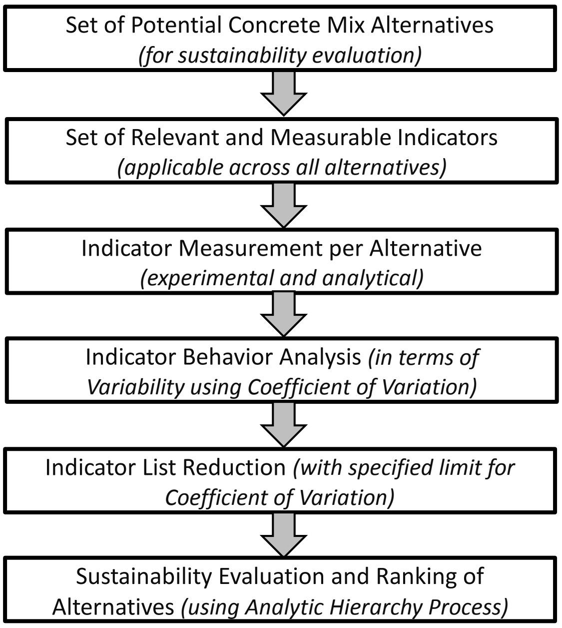

Fig.1 Methodological framework

Table 1 Mix proportion data

Mix	Proportions (kg/m^3)					
	W	C	FA	S	NA	RA
Control	171	342	0	746	1015	0
WB30-RA0	135	225	225	659	1067	0
WB30-RA50	135	225	225	659	533	478
WB30-RA100	135	225	225	659	0	957
WB375-RA0	135	180	225	721	1095	0
WB375-RA50	135	180	225	721	548	491
WB375-RA100	135	180	225	721	0	982
WB45-RA0	135	150	225	772	1103	0
WB45-RA50	135	150	225	772	552	495
WB45-RA100	135	150	225	772	0	989

2.2 Relevant and Measurable Indicators

The relevant indicators were subsequently identified after determining the alternatives. To demonstrate the usability and effect of indicator reduction, an initial exhaustive set of indicators (S1) was necessary. To form this set, the previous work by the authors, aggregating 65 sustainable concrete indicators to a causal framework was utilized. The framework forms the driving force-state-impact relation, while integrating the pillars of sustainability: environment, society, economy [5]. Two qualifying selection criteria corresponding to United Nations Commission on Sustainable Development (UN-CSD) guide [6] were used to justify indicator inclusion: relevance to the analysis and measurability.

The indicators in S1 are in Table 2 with nomenclature identical to the source [4]. Since measurability is one qualifying criterion for indicator inclusion, indicators that cannot be measured at the time of the analysis (e.g., equipment limitations or unavailability), or cannot be derived using engineering relationships were eventually excluded. For instance, the unavailability of inventory data relevant to ecotoxicity potential led to the removal of its indicator. Additionally, the causal relationship of the indicators, a subset of the original framework is shown in Fig. 2.

Table 2 Indicators in the S1 set

SCI ID	Indicator Name	Sustainability Pillar			Desired Behavior
		En	So	Ec	
2	Primary raw materials consumption	○	○	○	D
3	Water consumption	○	○	○	D
4	Recycled materials content	○	○	○	I
5	CO_2 emissions	○			D
6	SOx emissions	○	○		D
7	NOx emissions	○	○		D
8	Particulate matter emissions	○			D
17.01	Compressive strength	○		○	I
17.04	Young's modulus	○		○	I
23	Cost of raw materials			○	D
25	Cost of recycled materials			○	D
28	Global warming potential	○			D
29	Acidification potential	○			D
30	Photochemical ozone creation potential	○			D
31	Eutrophication potential	○			D
34	Human toxicity potential		○		D
37	Structural safety		○		I
40	Production cost			○	D

(note: En = environment, So = Society, Ec = Economy, I = increase, D = decrease)

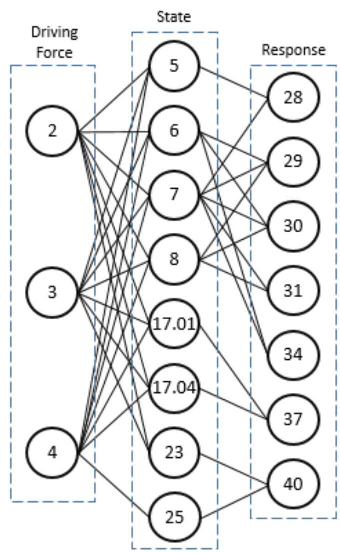

Fig.2 Causal indicator framework

2.3 Indicator Measurement

Indicators included in S1 were measured either through experimentation or analytical calculation. Their values were determined as follows: 10 indicators were derived analytically using environmental inventory data (SCI 5, 6, 7, 8, 28, 29, 30, 31, 34); three were computed using the mix proportion data (SCI 2, 3, 4); three were derived from material cost relationship (SCI 23, 25, 40); two were obtained experimentally (SCI 17.01, 17.04), and one was computed using an arbitrary beam (SCI 37) of cross-section 150mmx200mm using the compressive strength and Young's modulus. SCI 37 was simplistically represented as the nominal moment capacity of the arbitrary beam. The inventory data used to calculate the values of the indicators is in Table 3. The unit costs of materials were adopted from the time when the original work was executed [5].

Table 3 Inventory data

Material	SCI 5 (kg/t) [7]	SCI 6 (kg/t) [7]	SCI 7 (kg/t) [7]	SCI 8 (kg/t) [7]	Unit Cost (JPY/kg)
C	766.6	0.12200	1.55000	0.035800	9.60
S	3.7	0.00860	0.00586	0.001990	1.55
NA	2.9	0.00607	0.00415	0.001410	1.32
FA	19.6	0.00620	0.00754	0.001250	4.00
RA	3.1	0.00127	0.01080	0.000655	0.62
W	-	-	-	-	0.15
Conversion of State to Impact Indicators [8]					
	SCI 28	SCI 29	SCI 30	SCI 31	SCI 34
SCI 5	1.000	-	-	-	-
SCI 6	-	0.043	1.000	-	0.096
SCI 7	-	0.028	7.000	0.130	1.200

2.4 Indicator Behavior Analysis

(1) Normalization

Since the indicators are expressed in different units of measurement, normalization was performed to render them comparable. The normalization method used is analogous to the distance to reference, which measures the relative position of an indicator vis-à-vis a reference point [9]. The indicator values of the control mix were used as the reference. Normalized values (N_A), were computed using the following expression with the reference set to 1.00:

$$N_A = \begin{cases} 1 + abs\left[\frac{I_i - I_r}{I_r}\right], \textit{Positive contribution} & (1.1) \\ 1 - abs\left[\frac{I_i - I_r}{I_r}\right] \textit{Negative contribution} & (1.2) \end{cases}$$

where:

I_i : is the indicator value;

I_r : is the indicator reference value;

abs : means absolute value.

Eq. 1.1 holds if an indicator reflects the desired behavior shown in Table 2 with respect to the reference mix, considered to contribute positively to the sustainability of the concrete mix, otherwise Eq. 1.2 applies. However, while the purpose of normalization is comparability of disparate values, it imparts uncertainty into the analysis because transformation does not reflect the original meaning of the indicator value. Due to space limitation, the context of uncertainty related to normalization is not discussed here (refer to [9] for additional discussion).

For SCI 2 and 4, I_r is the sum of the reference values of SCI 2 and 4; and for SCI 23 and 25, I_r is also the sum of the reference values for SCI 23 and 25. In other words, for these particular pairs of indicators, the reference value is the sum of primary and recycled materials of the reference mix. This is because the recycled materials act as a replacement for the primary raw materials for this data set.

(2) Coefficient of Variation

The coefficient of variation was used as a determining factor to exclude an indicator from S1 to form a reduced set, SR. The coefficient of variation (COV) in statistics is the standard deviation divided by the mean of the dataset, which is a measure of relative variability, expressed in percent or fractional form. This is useful in comparing the behaviors of various sets of observations, as in comparing the relative variability of different indicators. The coefficient of variation was computed after normalization was performed. An indicator with small COV suggests that the indicator's data is less varied compared to others. In contrast, higher COV value implies that indicator behavior is more sensitive to the changes in each alternative (e.g. replacing NA with RA), signifying that it is a dominant indicator, and may have a higher influence to the sustainability analysis.

2.5 Reduced Set of Indicators

Three reduced sets were generated using COV as eliminating factor: (1) indicators with COV greater than 0.05, (2) indicators with COV greater than 0.10, and (3) indicators with COV greater than 0.15. These sets were compared to S1 in terms of the sustainability rating of the various mix alternatives.

2.6 Sustainability Rating and Ranking

Analytic hierarchy process (AHP) was used to assess the sustainability rating of each alternative. The method is used to derive ratio scales from both discrete and continuous paired comparisons [10]. AHP has been explored in the area of concrete sustainability as a way to rank the different set of alternatives [11], similarly, it is utilized here to rank the alternatives to characterize the effect of eliminating indicators.

The complete AHP model employed is shown in Fig. 3. The hierarchical diagram is composed of the goal, which is sustainable concrete, and the criteria, which served as the basis to compare the potentially sustainable concrete mix alternatives. The criteria are subdivided into two categorical levels, one representing the pillars of sustainability, and the other containing the indicators. Additionally, in AHP, weights can be applied to various alternatives; however, in this analysis, equal weights were assigned to the elements to isolate the effect of indicator reduction technique.

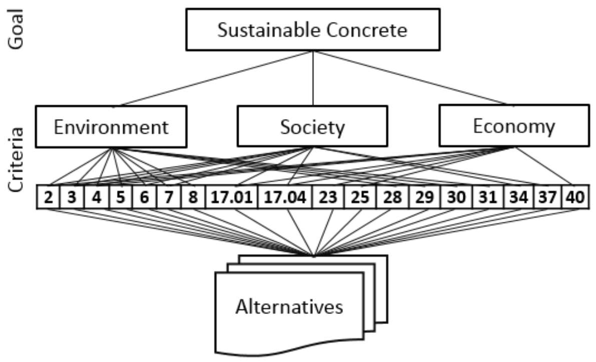

Fig.3 Hierarchical diagram for AHP calculation

3. RESULTS AND DISCUSSION

3.1 Indicator Behavior

The normalize indicator values are reflected in Table 4, including the COV per indicator data set. The raw values of the indicators were not shown due to space limitations. The normalized value implies the deviation of an indicator from the reference value, which was set to 1.00. The normalized value less than unity means that the variables of the experiment negatively contributes to the sustainability rating of a particular concrete mix alternative. On the other hand, a normalized value greater than unity means that the variables of the experiment positively contribute to the sustainability rating of an alternative concrete mix.

The values of the COV communicate the comparative variability of indicators within the data set, which was used to identify indicators with high sensitivity to the variables of the experiment. Comparing the COVs, it is apparent that the compressive strength (SCI 17.01) is the most affected property as a result of varying the amount of RA replacements and the W/B ratios, with COV = 0.23. Naturally, this variability propagated to SCI 37 with equivalent COV to SCI 17.01, since it was derived using the values of the compressive strength that only reflects of this relationship. Additionally, SCI 2 and 4, also show high relative sensitivity to material manipulation. These observations justify that COV is an effective tool to discern indicators most affected when experimental variables were operationalized. Therefore, SCI 17.01, 37, 2 and 4 are the dominant indicators based on this argument.

In contrast, the COV of SCI 3 is the lowest, because between alternatives, except for the control, the amount of water remained constant (135kg/m^3). This suggests SCI 3 does not provide a significant basis to compare the alternatives. Thus indicators with low COV can be discriminated as playing trivial roles in the analysis.

3.2 Reduced Indicator Set

The indicators in S1 were screened by applying the COV values greater than 0.05, 0.10, and 0.15, retaining progressively those indicators expressing higher behavior variation, as shown in Fig. 4. For this case, the resulting COV ≥ 0.05 elimination produced a set identical to S1. The other reduced sets contain 15 indicators ($SR_{0.10}$), and five indicators ($SR_{0.15}$), for COV limits greater than or equal to 0.10, and 0.15, respectively. From this, only three sets of indicators were considered for AHP calculation: S1, $SR_{0.10}$, and $SR_{0.15}$. The retained indicators per reduced set are reflected in Table 4 marked with '○'.

The trend reflected in Fig. 4 provides an insight

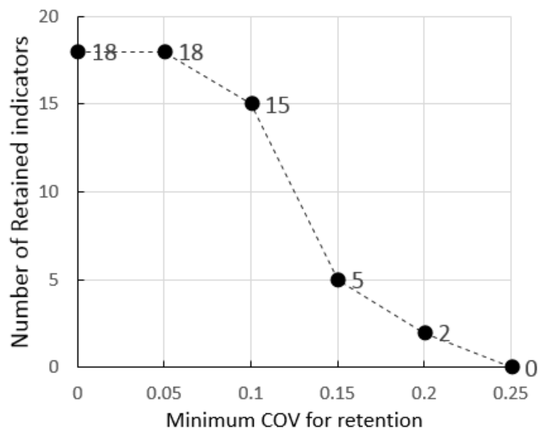

Fig.4 Retained indicators by COV elimination

Table 4 Normalized indicator values per concrete mix, the coefficients of variation for each indicator, and the retained indicators of the reduced sets

	SCI																	
Alternatives	2	3	4	5	6	7	8	17.01	17.04	23	25	28	29	30	31	34	37	40
Control	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
WB30-RA0	1.07	1.21	1.11	1.32	1.25	1.33	1.26	1.12	0.94	1.21	0.84	1.32	1.32	1.32	1.33	1.33	1.16	1.05
WB30-RA50	1.33	1.21	1.33	1.32	1.29	1.34	1.11	1.12	0.86	1.33	0.79	1.32	1.33	1.33	1.34	1.33	1.20	1.12
WB30-RA100	1.58	1.21	1.56	1.32	1.34	1.34	0.95	0.96	0.72	1.45	0.74	1.32	1.34	1.34	1.34	1.34	1.08	1.19
WB375-RA0	1.05	1.21	1.09	1.45	1.34	1.46	1.36	0.95	0.87	1.26	0.88	1.45	1.44	1.45	1.46	1.46	1.00	1.13
WB375-RA50	1.31	1.21	1.32	1.45	1.39	1.47	1.20	0.75	0.75	1.38	0.82	1.45	1.45	1.46	1.47	1.47	0.81	1.21
WB375-RA100	1.57	1.21	1.55	1.45	1.44	1.47	1.04	0.73	0.67	1.51	0.77	1.45	1.47	1.47	1.47	1.47	0.82	1.28
WB45-RA0	1.04	1.21	1.07	1.54	1.40	1.55	1.43	0.65	0.78	1.29	0.90	1.54	1.53	1.55	1.55	1.55	0.66	1.19
WB45-RA50	1.30	1.21	1.31	1.54	1.45	1.55	1.27	0.84	0.74	1.42	0.84	1.54	1.54	1.54	1.55	1.55	0.93	1.26
WB45-RA100	1.56	1.21	1.54	1.54	1.50	1.56	1.10	0.54	0.64	1.54	0.79	1.54	1.55	1.55	1.56	1.56	0.56	1.33
COV	0.18	0.06	0.17	0.12	0.11	0.12	0.14	0.23	0.15	0.12	0.09	0.12	0.12	0.12	0.12	0.12	0.23	0.09
$SR_{0.10}$	○		○	○	○	○	○	○	○	○		○	○	○	○	○	○	
$SR_{0.15}$	○		○					○	○								○	

regarding the representativeness of the reduced indicator sets in terms of concrete sustainability. Since it was argued that some indicators provide less important ground for comparing alternatives, it follows, therefore, that a reduced set may be used in lieu of an exhaustive set to evaluate the sustainability of concrete without losing representativeness. For instance, reducing S1 to $SR_{0.10}$, where only the very least varying indicators are omitted (COV < 0.10), justifies that $SR_{0.10}$ remains to be a valid set. This supports the idea that not all indicators are sensitive to the experimental variables, in this case, the percentage of RA replacements and W/B ratios. COV elimination, additionally, reduces the complexity of the analysis. However, as more stringent COV limit is applied, as in $SR_{0.15}$, more indicators are also discriminated as less important, which might undermine the representativeness of the indicator set. This suggests the need to strike a balance between reducing the complexity by using fewer indicators and the representativeness of the set, in short, to come up with less but valuable number of indicators.

3.3 Sustainability Rating and Ranking by AHP

(1) Effect on Sustainability Rating of Alternatives

The AHP results describe the effect of using a reduced set of indicators on sustainability rating of concrete mix alternatives, summarized in Table 5. The values are the relative weights after performing AHP; these are also normalized with respect to the control mix, set to unity. The normalized AHP weights greater than the reference signify that the particular alternative is more sustainable than the control mix.

The result using S1 implies that all alternatives are more sustainable than the control mix, which is similar to the result of $SR_{0.10}$, while only one alternative qualifies as less sustainable in $SR_{0.15}$, which is WB45-RA0. Furthermore, there is a noticeable increase in the disparity between normalized AHP values differentiating the alternatives into two as indicator reduction progressed: those with normalized values moving closer to the reference, and those retained relative predominant values. Normalized AHP values close to the reference imply that in terms of sustainability, an alternative is equivalent to the control mix. AHP points that WB30-RA100 and WB30-RA50 are the predominant alternatives, retaining consistently high relative normalized values. By inspecting the indicators of $SR_{0.15}$, the two predominant alternatives show high values for SCI 2 and 4, similar values for SCI 17.01 and 37, and comparable values for SCI 17.04 with respect to the control mix. This can be attributed to a combination of low W/B ratio, equal to 0.30, and high RA replacements of both mixes.

(2) Effect on the Ranking of Alternatives

The ranking of the alternatives in Table 5 shows the effect of indicator reduction. More indicators retain their ranks from S1 to $SR_{0.10}$, compared to their ranks from S1 to $SR_{0.15}$. This is an indication that the ranking of alternatives is less sensitive to the elimination of less varying indicators. There are also two noticeable divisions in the ranking: alternatives that consistently belong to top ranks (1-5), and those consistently within the bottom ranks (6-10), across indicator sets. Using the indicators in $SR_{0.15}$ and the values in Table 4 to explain this divide, it is observable that the indicators in the top ranks have very high values in SCI 2 and 4, due to the high percentage of recycled aggregate replacement, from 50% to 100%. This justifies that high RA replacement contributes more to the sustainability rating of a concrete mix. However, in the case of WB375-RA50, despite having high values in SCI 2 and 4, it is dragged into the lower rank because of the complementary effect of its lower performing indicators (e.g., SCI 17.01 and 37), neutralizing the benefits of replacing NA with 50% RA. Additionally, between the alternatives within the top ranks, the ranking implies that lower W/B ratios contribute positively to sustainability. This is evident in WB30-RA100, ranked as the most sustainable alternative. This particular mix scores the highest in SCI 2 and 4 resulting from a combination of low W/B ratio and replacing NA with 100% RA. The resulting compressive strength and the structural safety of this mix is also comparable to the control, which further justifies this outcome.

4. CONCLUSIONS

The application of the indicator reduction technique to concrete sustainability evaluation elicits following conclusions:

(1) COV analysis identified SCI 17.01, 37, 2 and 4 as

Table 5 Result of AHP calculation per indicator set

Series/ Alternatives	S1			$SR_{0.10}$			$SR_{0.15}$		
	Relative Weight	Normalized	Rank	Relative Weight	Normalized	Rank	Relative Weight	Normalized	Rank
Control	0.0866	1.0000	10	0.0863	1.0000	10	0.0927	1.0000	9
WB30-RA0	0.0990	1.1432	8	0.0994	1.1518	7	0.0992	1.0701	6
WB30-RA50	0.1028	1.1871	5	0.1043	1.2086	3	0.1098	1.1845	2
WB30-RA100	0.1038	1.1986	1	0.1057	1.2248	1	0.1154	1.2449	1
WB375-RA0	0.0995	1.1490	7	0.0988	1.1448	8	0.0928	1.0011	8
WB375-RA50	0.1003	1.1582	6	0.0998	1.1564	6	0.0978	1.0550	7
WB375-RA100	0.1038	1.1986	2	0.1044	1.2097	2	0.1081	1.1661	3
WB45-RA0	0.0968	1.1178	9	0.0944	1.0939	9	0.0827	0.8921	10
WB45-RA50	0.1037	1.1975	3	0.1035	1.1993	4	0.0995	1.0734	5
WB45-RA100	0.1037	1.1975	4	0.1034	1.1981	5	0.1019	1.0992	4

the dominant indicators, showing high relative variability across alternatives.

(2) Eliminating the very least varying indicators does not necessarily affect the representativeness of the reduced set; however, representativeness might be affected if higher COV is set as a limit for elimination.

(3) The disparity in the normalized AHP sustainability weights between alternatives becomes more prevalent with progressive indicator reduction, leading to the determination of the predominantly more sustainable concrete mix alternatives relative to the control. Additionally, the sensitivity of the ranking of alternatives is only a reflection of the reduction process, with more alternatives retaining their relative rank in the reduced sets from SR1 to $SR_{0.10}$ than from S1 to $S_{0.15}$.

(4) The concrete sustainability analysis concludes that a combination of high RA replacement and low W/B ratio are the primary factors contributing positively to the sustainability, therefore, between the analyzed alternatives, WB30-RA100 is relatively the most sustainable alternative.

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