- Technical Paper -

ASSESSMENT OF CONCRETE SUSTAINABILITY USING SOCIAL PERSPECTIVES AND ANALYTIC HIERARCHY PROCESS

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ABSTRACT
A social study was performed on how to assess concrete material sustainability in the Japanese concrete industry. The perspectives were converted to weights using Analytic Hierarchy Process, a multi-criteria decision-making tool, and the sustainability of several concrete mixtures was compared. It was found that fly ash concrete mixes with normal or recycled aggregates had the highest weights, and between these mixes the reduction in strength from using recycled aggregates was offset by the value of recycled materials. The absolute sustainability of the mixes could also be assessed.
Keywords: sustainability, Analytic Hierarchy Process, fly ash, recycled aggregate, social study

1. INTRODUCTION

Sustainable development is commonly defined as development which "meets the needs of the present without compromising the ability of future generations to meet their own needs" [1]. However, although this definition was established over 20 years ago, there has been little progress in developing a general-purpose definition. One means of considering sustainability is as the integration of the "three pillars" of sustainability: the environment, society, and the economy. This relationship is shown in Fig. 1, and illustrates the co-dependency between the three pillars; for example, the well-being of society depends on the well-being of the environment, and so forth.

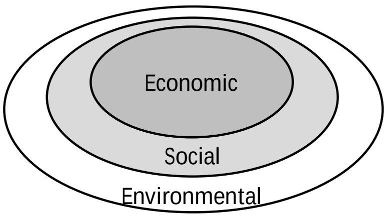

Fig.1 Visualization of sustainability [2]

Increased awareness of sustainability has led the concrete industry to consider its practice, looking particularly at the environmental impact. Approaches to reducing the industry's impact include increasing durability of concrete structures, utilizing the waste products of other industries as a replacement material, and the recycling of demolition waste back into the construction process [3]. Durable concrete materials utilizing waste and recycled materials could form the foundation of sustainable concrete practice but, just as sustainable development is only a concept and not a tangible plan of action, so too is it difficult to determine what constitutes "sustainable" for concrete materials. Although many proposals focus on durability and usage of recycled materials, there is oftentimes a trade-off between these two. Another problem with defining concrete sustainability is the diverse number of perspectives in the concrete industry. There are many stakeholder groups – from private and public owners to contractors and manufacturers – and each have their own perspectives and goals.

In this paper, how to assess concrete sustainability is considered as a multi-criteria problem which involves the input of the social perspectives of the Japanese concrete industry members. These perspectives are converted from importance factors to comparative weights using Analytic Hierarchy Process, and the comparative and absolute sustainability of several mixes with different approaches to concrete sustainability are examined.

2. SOCIAL STUDY ON SUSTAINABILITY OF CONCRETE MATERIALS

2.1 Summary of interview phase

A two-part social investigation on perspectives on sustainable practice in the Japanese concrete industry was conducted. The objective of this study was to first establish a general qualitative knowledge base and concept for sustainable concrete practice and materials using a top-down approach with in-depth interviews, then quantitatively investigate the importance given to different parameters and indicators for defining the sustainability of concrete materials with a bottom-up approach using surveys.

The first phase, which was conducted using a top-down approach with semi-structured interviews, investigated the perspectives of 13 members of different social groups in the Japanese concrete industry, as shown in Fig. 2.

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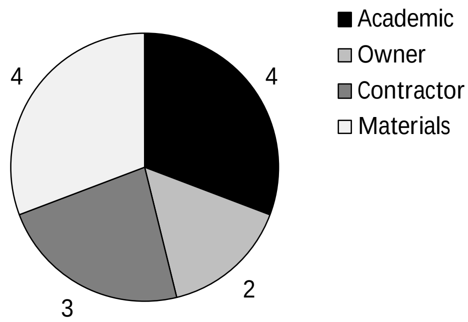

Fig.2 Interviewee distribution

The interview phase of the study found that, although people had a clear idea of their role in current practice in the Japanese concrete industry, and thus clear differences in goals, they all shared a similar concept for what sustainable practice should be [4]. Sustainable concrete practice could be divided into concrete engineering and sustainability components, as shown in Fig. 3, with evaluation criteria such as life cycle cost (LCC), durability, and life cycle CO_2 ($LCCO_2$); specific actions for implementing those criteria such as need for durability evaluation methods and the establishment of inventory data; and general actions such as the implementation of standardized codes for defining sustainable concrete practice, consideration of the full life cycle, and so forth.

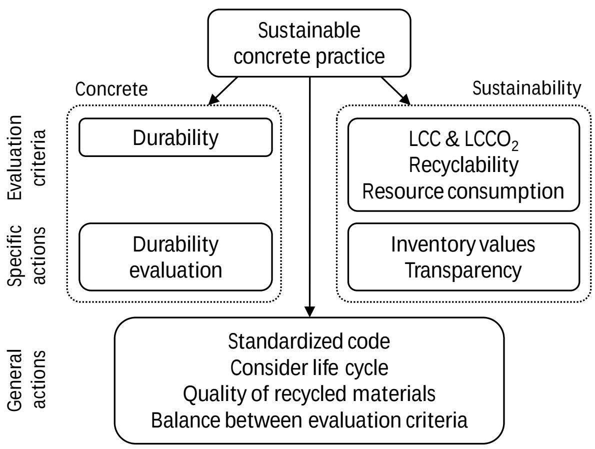

Fig.3 Concept for sustainable concrete practice

The reason all interviewees had the same general concept for sustainable concrete practice may be due to the lack of understanding of their role and responsibilities in practicing sustainability. When asked about current concrete practice, the interviewees had significantly different responses depending on their role in the manufacturing, production, and construction process; that is, their responsibilities for current practice are clearly outlined by experience, codes, guidelines, regulations, and so forth. However, because their roles and responsibilities in an industry practicing sustainability are vague, the interviewees only share an ideal concept of what sustainable practice might be without understanding what specific role they should serve. This is supported by the need to establish standardized codes and guidelines for different aspects of sustainable practice, such as life cycle cost analysis (LCCA) or calculation of $LCCO_2$ emissions, which would provide engineers with a clearer understanding of how to take action.

Since the interview phase gave a qualitative concept for sustainable practice, one objective of the following survey phase was to determine the quantitative balance between criteria for assessing the sustainability of concrete materials.

2.2 Survey respondents

The distribution of survey respondents is shown in Fig. 4. In total, 229 survey responses were received, with 47.2% in the owner group, 28.8% in the contractor group, 13.1% in the academic group, and 10.9% in the materials group. Respondents in the owner group came from private and public infrastructure owners such as railway and power companies and public agencies; in the materials group, respondents came from material producers such as fibers or bonding agents and from cement and admixture companies.

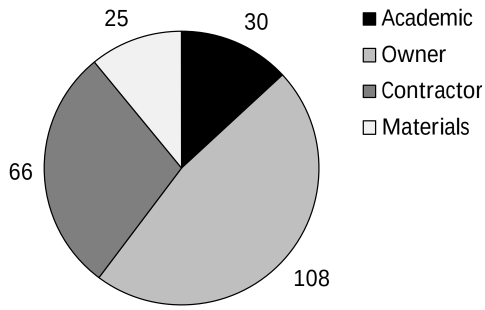

Fig.4 Distribution of survey samples

2.3 Survey contents

The survey contents included general background information, such as organization, and also evaluated the importance given to different concrete performance parameters and sustainability indicators for evaluating the sustainability of concrete materials. The importance was ranked on a scale of 1 to 4, where 1: no importance, 2: little importance, 3: some importance, and 4: high importance. The concrete performance parameters were taken from a list given by the Japan Society of Civil Engineers (JSCE), and the sustainability indicators were taken from the United Nations Committee on Sustainable Development's theme indicator framework.

2.4 Representativeness

It is statistically difficult to determine whether this sample size is representative of the Japanese concrete industry due to difficulties in defining the boundaries and population size and distribution. However, the results of the survey were found to correspond well with the results of the interviews, so the combination of the top-down approach taken in the interviews and the bottom-up approach taken in the surveys is used to establish representativeness of the social study's results.

2.5 Key aspects and variance analysis

From the survey results, five key aspects for assessing sustainable concrete practice were identified. Importance factors by social group are given in Table 1. These key aspects had the highest importance, with each rated "some" or higher. The key aspects cover three concrete parameters (strength, durability, and cost) and two sustainability indicators (environmental and economic). Following the UN's framework, environmental aspects include atmosphere (emissions, air pollution, etc.), land use, and so forth; economic aspects include production and consumption patterns (recycling), trade, and so on. Cost was selected as a concrete material property because the UN's framework for "economic" focuses more on general economic systems, whereas cost is a basic material property.

Table 1 Importance factors by social group

Aspect	Academic	Owner	Contractor	Materials
Strength	3.3	3.5	3.6	3.3
Durability	3.6	3.8	3.8	3.6
Cost	2.9	3.7	3.8	3.5
Environmental	3.4	3.4	3.4	3.2
Economic	3.2	3.4	3.6	3.4

It can be seen that there was some difference in the importance factors of the aspects between social groups. To clarify whether this difference was statistically significant or caused by variation within the sample groups, one-way analysis of variance (ANOVA) and post-hoc analysis (Scheffé's Method) were used.

There was no statistically significant difference (at 5% significance) between the social groups for any of the aspects except for "cost," where the importance factors of the owner, contractor, and materials groups were higher than the importance factor for the academic group, and the importance factor for the contractor group was also higher than that for the materials group. To resolve the difference in "cost" importance between social groups and establish a set of overall importance factors for the key aspects, the contractor's importance factor was selected because it was higher than that of the academic and materials groups and statistically the same as owner group. The final importance factors for the key aspects are summarized in Table 2.

Table 2 Final importance factors for key aspects

Aspect	Importance factor
Strength	3.5
Durability	3.8
Cost	3.8 (contractor)
Environmental	3.4
Economic	3.4

3. CONCRETE MATERIALS

3.1 Mix proportions

The relative and absolute sustainability of five different concrete mixes were examined to evaluate the balance between different material properties and performances. These concrete mixes are given in Table 3, and examine several different factors: the effect of water-binder ratio (30% vs. 50%), the effect of aggregate type (normal vs. recycled), the effect of fly ash replacement (none vs. 50%), and the effect of combining fly ash and recycled aggregates. Water (W), normal Portland cement (C), type-II fly ash (FA), river sand (S), normal aggregates (NG), and grade-L recycled aggregates (RG) were used.

Table 3 Mix proportions

Series	kg/m^3					
	W	C	FA	S	NG	RG
WB50-NA	171	342	-	746	1015	-
WB30-NA	165	550	-	624	1009	-
WB30-RA	165	550	-	624	-	905
WB30-NA-FA50	165	275	275	590	955	-
WB30-RA-FA50	165	275	275	590	-	856

3.2 Representative indicators

For each of the key aspects, a representative indicator was selected based on the available test results and appropriateness for the aspect. Compressive strength is the most widely-used representation of strength performance. Air permeability is a durability indicator which is often used for evaluating surface concrete durability. Cost is the basic cost per cubic meter of concrete. CO_2 emissions are used to represent the environmental aspect because CO_2 emissions belong to the "atmosphere" theme of the UN indicators and are widely used as the primary indicator of environmental impact of concrete. Finally, the percentage of recycled materials is used for evaluating the economic impact; this indicator comes from the "consumption and production patterns" UN indicator, which includes recycling and resource consumption.

3.3 Concrete properties

Table 4 gives the properties of the concrete mixes for the five representative indicators.

Table 4 Concrete properties summary

Series	Comp. strength (MPa)	Air perm. (cm/s×10^{-11})	Cost (yen/m^3)	CO_2 emissions (kg-CO_2/m^3)	Recycled materials (%)
WB50-NA	50.1	36.5	5810	267.9	0.0
WB30-NA	81.0	14.4	7610	426.9	0.0
WB30-RA	58.6	47.5	6828	426.7	37.2
WB30-NA-FA50	64.4	6.0	5945	221.2	12.0
WB30-RA-FA50	46.2	11.0	5205	221.0	47.2

The compressive strength and air permeability values were taken at 56 days from casting under water curing conditions. The costs were calculated using the mix proportions and material costs obtained from a catalog of material costs in Japan (Sekisan-shiryou). In the case of fly ash, the cost may vary so a private company was contacted and the cost of fly ash estimated based on their response. The cost for recycled aggregates was estimated from the price of recycled crushed stone used in road beds, and the cost of water was taken from the Tokyo Metropolitan Bureau Waterworks. The CO_2 emissions for each mix were determined from the mix proportions and the emissions per component material as given by JSCE [5]. Finally, the recycled materials volume was calculated as the percent volume per cubic meter occupied by fly ash and/or recycled aggregate.

4. AHP ASSESSMENT OF MATERIALS

4.1 AHP methodology

Analytic Hierarchy Process is a multi-criteria framework developed by Thomas L. Saaty for making complex decisions. The premise of AHP is to model a decision-making problem as a hierarchy composed of quantifiable elements and their relations and alternatives towards a goal [6]. The weight of the elements towards the goal is determined by comparing elements against each other in pairs using quantitative or qualitative judgment values, which are converted to numerical values that can be used to determine weights for the elements in the hierarchy and allows comparison between different elements. Weights can be similarly applied to the various alternatives for achieving the goal, based upon the weights of the elements in the hierarchy and the characteristics of the alternatives, and a decision for achieving the goal can then be made by analyzing the weights of the different alternatives.

4.2 Assessment hierarchy

The hierarchy for assessing the sustainability of the concrete materials can be constructed as shown in Fig. 5. In this hierarchy, the "goal" is sustainable concrete, the different aspects make up the "elements" of the hierarchy, and the concrete mixes being investigated are the "alternatives" for meeting the goal.

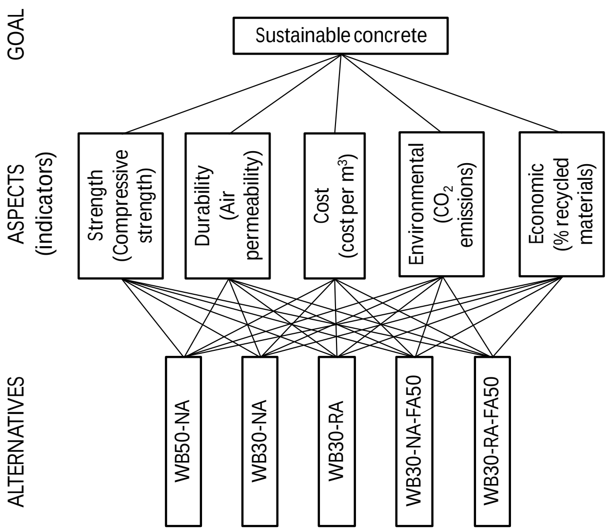

Fig.5 AHP hierarchy with aspects and alternatives

4.3 Pairwise comparisons & weight calculation

Pairwise comparisons are a fundamental aspect of AHP and are necessary to normalize and compare criteria with different scales or units. For quantitative data values, such as the importance factors for the aspects and the strength, cost, CO_2 emissions, and amount of recycled materials for the material properties, the pairwise comparison is conducted by normalizing only. The durability aspect alone is treated as qualitative because the relationship between air permeability and durability is not linear, so durability will be classified as "low," "moderate," and "high."

4.4 Weights of assessment criteria

The weights of each aspect for assessing the sustainability of concrete were calculated and are given in Table 5. Following the trend of the importance factors, it can be seen that more weight is given to durability and cost, with the least weight given to environmental and economic. Since the difference between the importance factors was not so great (because the factors with the highest importance were specifically selected), the difference in weights between the aspects is not very large.

Table 5 Weights for sustainable concrete aspects

Aspect	Weight
Strength	0.196
Durability	0.212
Cost	0.212
Environmental	0.190
Economic	0.190

4.5 Relative weights of concrete materials

The relative weights of each material for each property are shown in Table 6. For strength, WB30-NA has the most weight at 27.2%. The highest weight for durability is given to the WB30-NA and WB30-NA/RA-FA50 mixes at 25.3%, and for cost the highest is WB30-RA-FA50 at 23.6%. For the environmental aspect, the two fly ash concrete series have the highest weight at 25.9%. Finally, for the economic aspect WB30-RA-FA50 has the highest weight at 28.6%.

Table 6 Relative weights for concrete materials

Series	Strength	Durability	Cost	Environmental	Economic
WB50-NA	0.159	0.113	0.216	0.214	0.151
WB30-NA	0.272	0.253	0.161	0.134	0.151
WB30-RA	0.197	0.127	0.180	0.134	0.240
WB30-NA-FA50	0.217	0.253	0.207	0.259	0.172
WB30-RA-FA50	0.155	0.253	0.236	0.259	0.286

4.6 Final weights

The final value for each material is the sum of the products of the material's relative weights for each property (Table 6) and weights of each property (Table 5). Repeating this calculation for each material gives the final values shown in Table 7. Based on the weights as selected by the social groups and the concrete properties of each material, WB30-RA-FA50 has the highest value for meeting the goal of sustainable concrete, at 23.8%, and WB30-NA-FA50 has the second-highest value at 22.2%. The lowest value is for WB50-NA, at 17.0%.

Table 7 Final values by material

Series	Value
WB50-NA	0.170
WB30-NA	0.195
WB30-RA	0.175
WB30-NA-FA50	0.222
WB30-RA-FA50	0.238

5. VISUALIZATION OF CONCRETE MATERIAL SUSTAINABILITY

5.1 Visualizing absolute sustainability

When developing concrete materials, it may be useful to visually observe the distribution of weights carried by different materials for decision-making processes. The final values given in Table 7, however, are only representative of the relative sustainability and don't give any indication of the absolute sustainability. It is necessary to establish a baseline which can provide a reference state for sustainable concrete.

5.2 Setting a baseline condition

Setting a baseline for the concrete industry is not easy because, unlike ecological systems, there is no historical reference point which can be labeled as a "sustainable" state to return to. Rather, the baseline condition should be set by looking forward and considering the direction the industry should move. It has already been established that the concrete industry needs to become more sustainable and reduce its environmental impact from its current state. Therefore, sustainable concrete should look to meet or exceed the performance of the general-use concrete in the areas given by the indicators.

5.3 Visualization with baseline condition

The WB50-NA series can be considered representative of the general-use concrete mix proportions and performances. To construct the baseline condition, the weighted performance values for each concrete mix were normalized by the WB50-NA series values. The results are shown in Fig. 6.

Reducing the water-cement ratio from 50 to 30 (WB30-NA) greatly increases the strength and durability values, but reduces the cost and environmental values with respect to the baseline condition. The replacement of normal aggregate with recycled aggregate (WB30-RA) reduces strength and

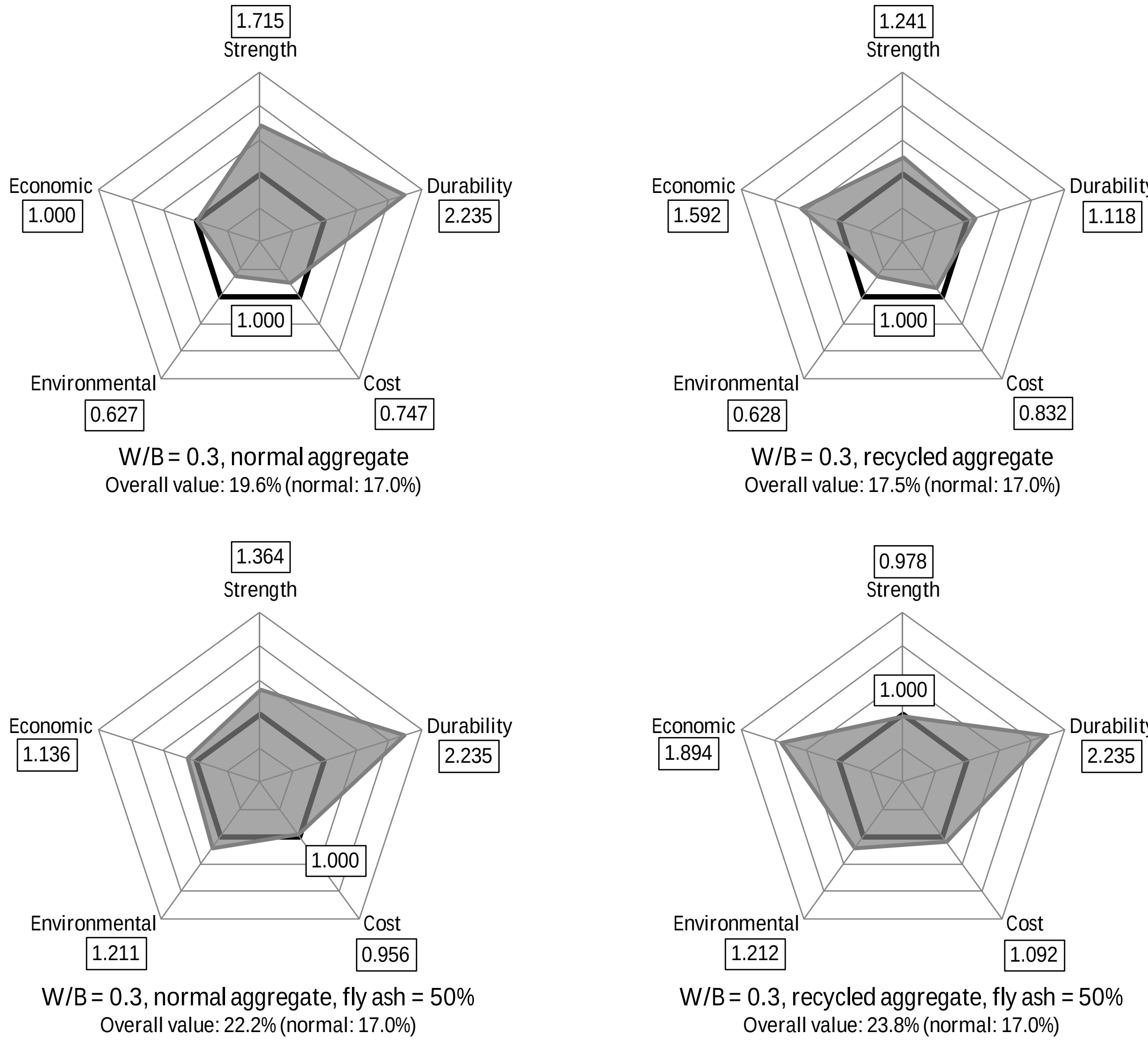

Fig.6 Weights of concrete mixes normalized by general-use concrete

durability (but still exceeds the baseline), while improving the economic value. Both the WB30-NA/RA series have overall higher sustainable value than the baseline condition, but for different values. The same can be said of the two fly ash mixes. Replacing 50% of the cement with fly ash (WB30-NA-FA50) decreases strength but increases cost, environmental, and economic values. Replacing the normal aggregates with recycled aggregates (WB30-RA-FA50) reduces strength but greatly increases the economic value. Comparing the two fly ash series, it can be seen that the recycled aggregate concrete is preferred overall, which shows that the strength reduction was balanced by the improvement in economic value.

6. BARRIERS TO IMPLEMENTATION

It can be clearly seen that the fly ash concretes are the preferred alternatives when using the input importance factors selected by the social study, but these materials have not seen wide use. Perhaps the most relevant barriers to the implementation of these materials are related to the emphasis on fast construction schedule and inability to evaluate additional value of concrete in bidding contracts. The test results used in the AHP analysis were taken at 56 days; however, the overwhelming majority of construction projects specify high early-age strength so that construction can proceed quickly. The strength development of fly ash concrete is slower than normal-strength concrete, so it takes longer to reach specified strength levels. This could be overcome by specifying strength at later ages or utilizing innovative construction systems, such as precast. In addition, the current bidding system does not consider the additional benefits of fly ash concrete, such as reduced CO_2 or enhanced durability, since most emphasis is placed on strength. This barrier must be overcome by institutional changes and the implementation of durability-based planning and design.

7. CONCLUSION

(1) Sustainable concrete practice could be divided into concrete and sustainability aspects, with LCC, durability, $LCCO_2$, recyclability, and others indicated as important points for sustainable concrete practice in general.

(2) From a survey on the importance of different criteria for assessing sustainable concrete, durability and cost were given the highest importance, followed by strength, environmental impact, and economic impact.

(3) The relative sustainability of concrete mixes with varying water-binder ratios and usage of fly ash and recycled aggregates was evaluated by using the importance factors from the survey and actual experimental results as input into AHP. The concrete with the highest value for sustainable concrete had a water-binder ratio of 30%, recycled aggregate, and 50% fly ash. The general-use concrete with water-binder 50% and normal aggregates had the lowest value.

(4) The general-use concrete was established as the baseline for judging absolute sustainability. Normalizing the weights of the materials by the weight of the general-use concrete illustrated the absolute sustainability of each material by aspect. Replacing normal aggregates with recycled aggregates reduced strength but increased the environmental value, and overall the trade-off was roughly equal.

(5) Although these materials are shown to have equal or superior performance to the general-use concrete, they haven't been practically implemented due to institutional barriers such as emphasis on fast construction schedule or inability to evaluate additional value, like durability or environmental impact.

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REFERENCES

[1] United Nations, "Report of the world commission on environment and development," General Assembly Resolution 42/187, 1987.

[2] Cornell, "Cornell University sustainable campus," (online), retrieved 2009 Dec. 24: http://www.sustainablecampus.cornell.edu/csi.cfm

[3] Mehta, P.K., "Concrete technology for sustainable development," Concrete International, Vol. 21, No. 5, 1999, pp. 47-53.

[4] Henry, M. and Kato, Y., "Perspectives on sustainable practice and materials in the Japanese concrete industry," 8th International Symposium on New Technologies for Urban Safety of Mega Cities in Asia, Incheon, Korea, 2009.

[5] "Recommendation of environmental performance verification for concrete structures (draft)," JSCE Task Force on Environmental Aspects, 2006.

[6] Saaty, T.L., "Decision making for leaders: the analytic hierarchy process for decisions in a complex world," Pittsburg: RWS Pubs., 1999.

[7] Trick, M.A., "Analytic hierarchy process – class notes," Carnegie Mellon Univ. Tepper School of Business (online), retrieved 2009 Dec. 26: http://mat.gsia.cmu.edu/classes/mstc/multiple/node4.html