# Simplified Triple Bottom Line Assessment for New concrete Materials During the Development Process



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# SIMPLIFIED TRIPLE BOTTOM LINE ASSESSMENT FOR NEW CONCRETE MATERIALS DURING THE DEVELOPMENT PROCESS

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***ABSTRACT*:** A method for assessing the sustainability of a concrete material would be useful for guiding the development process towards "green" concretes which can help improve sustainable practice in the concrete industry. This paper proposes a simplified triple bottom line assessment method based upon three sustainable criteria: economic, environmental, and social impacts. The cost of materials, the cost of $CO_2$ emissions related to the concrete materials, and the disposal cost of waste and recycled materials are used as the calculation criteria. When performing a trial calculation on normal, fly ash, and fly ash with recycled aggregate concretes, it was found that the triple bottom line cost was significantly affected by the discount from the disposal of recycled materials. However, the variability of the cost of fly ash and the global value of $CO_2$ may have a significant effect on how the sustainability of concrete materials is estimated.

***KEYWORDS***: triple bottom line, sustainability, life cycle cost, life cycle assessment, concrete materials

## 1. INTRODUCTION

Environmental deterioration and the increasing frequency of weather-related disasters such as hurricanes and floods have emphasized the importance of adopting sustainable practices in all sectors of the economy. For the concrete industry in particular, sustainability represents both a challenge and an opportunity.

The production of one ton of Portland cement, the primary ingredient in concrete, consumes large amounts of fossil fuels and energy, and also releases approximately one ton of carbon dioxide ($CO_2$), a greenhouse gas (GHG). Some researchers estimate the manufacture of Portland cement is responsible for roughly 7% of the world's total $CO_2$ emissions (Malhotra, 1999). When including the natural resources necessary for producing concrete, the concrete industry is possibly the largest consumer of these resources in the world. Unfortunately, the demand for Portland cement and concrete cannot be reduced for the foreseeable future due to economic growth and investment in infrastructure construction, so it is necessary to take a different approach to reducing environmental impact. Mehta (1999) proposed three elements for shifting the concrete industry towards sustainable practice: reducing the consumption of concrete-making materials, preferably by replacing them with industrial waste or recycled products; enhancing the durability of new concrete construction; and adopting a holistic approach in both technology and education.

The development and adoption of new materials is an essential part of this paradigm shift, particularly for reducing resource consumption and improving structural durability. A framework for the development of sustainable concrete materials, such as that shown in Figure 1, may be a helpful tool for innovators working in the field of concrete materials. This framework visualizes the development of a new technology as the transformation of media into an artifact by the transcription of design information (Yoshida & Yashiro, 2007). For "green" concrete, this design information should combine engineering knowledge and experience with sustainable criteria, and the media should be selected based upon sustainable values (Henry & Kato, 2008).

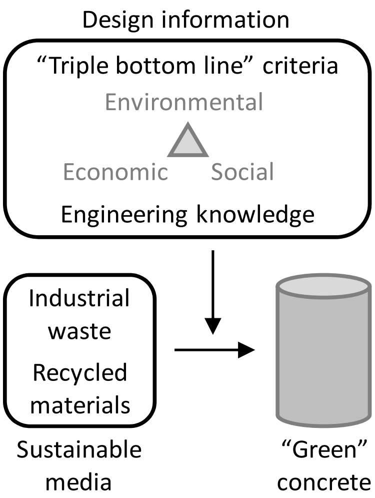


Figure 1 Developing sustainable concrete materials

Applying this framework, the goal of new material development should be to produce "green" concretes with sustainable characteristics. However, there is no clear methodology for assessing sustainability. When creating a material with more traditional characteristics such as strength, durability, or workability, standardized tests for evaluating those characteristics are applied to ensure accuracy, comparability, and reproducibility of results. Furthermore, such tests often use simplified methodologies based upon a set of assumptions. Without this simplification, it would be difficult and time-consuming to conduct practical, full-scale tests for every possible experimental case.

The essence of sustainable development is the "triple bottom line" of economic, environmental, and social impacts. Research has already been conducted within the concrete industry to evaluate some of these impacts: life cycle cost analysis (LCCA) has been used to evaluate the life cycle cost (LCC) of a structure over its service life, and life cycle assessment (LCA) is a tool for evaluating the environmental impact related to the construction and maintenance of a structure. However, these studies are typically highly detailed and dependent on case studies and local conditions, making them difficult to apply to the relatively simple case of a material under development.

### 1.1 Objectives

In order to evaluate the sustainability of new concrete materials, this paper proposes a simplified triple bottom line (TBL) assessment method. Existing models for evaluating economic (LCC) and environmental (LCA) impacts will be reviewed, and possible social impacts of concrete will be discussed in order to develop a social impact assessment method for concrete. The simplified TBL assessment method will then be proposed to provide a means for evaluating the sustainability of concrete materials during the development process. Finally, a trial calculation involving three different concrete mixtures will be conducted to understand how different factors affect the TBL cost.

## 2. TBL CRITERIA

### 2.1 Life cycle cost

LCC is the total cost for construction, operation, maintenance, and demolition over a structure's service life. Utilizing LCCA to determine the LCC of different design alternatives can provide a better comparison of the eventual, total cost rather than simply looking at initial design and build estimates, and provides a quantitative means of communicating life-cycle value to the public or client. It can also be used to compare different maintenance schemes depending on their performance and cost. LCC is calculated according to Equation 1.

$$LCC = C_A + C_U \quad (1)$$

Where $C_A$ is agency costs, and $C_U$ is user costs.

The agency costs can be split into two general categories: the initial cost for construction and the costs associated with maintaining the structure. Initial cost typically includes the costs for design and construction. Maintenance includes a variety of costs, such as inspection, repair, strengthening, and so forth. Maintenance is driven by deterioration of the structure under environmental or loading conditions, and repair is required when the performance reaches or exceeds a given safety limit. Strengthening is also necessary when the loading on the structure is estimated to exceed the design load-carrying capacity. These maintenance-related costs occur to keep structural performance above a certain level, so the controlling factor, such as environmental deterioration or earthquake resistance, can change depending on the location, changes in design codes, and so forth.

For triple bottom line assessment, user costs will be assumed to be part of the social impact, so further discussion will be given in Section 2.3.

### 2.2 Life cycle assessment

An LCA is performed in order to evaluate the potential environmental impact of a product over its service life. According to ISO (2006), there are four phases to conducting an LCA: goal and scope definition, inventory analysis, impact assessment, and interpretation. The scope includes the system boundaries and the level of detail, and varies depending on the study matter. Life cycle inventory gathers the input and output data relevant to the system being studied. Impact assessment evaluates the environmental significance of the results of the life cycle inventory. Finally, life cycle interpretation is for understanding the final assessment results in the context of the system and its environment.

For concrete, environmental impact is typically quantified by the $CO_2$ emission and energy consumption related with the different materials and phases of the concrete structure's life cycle (Fig. 2).

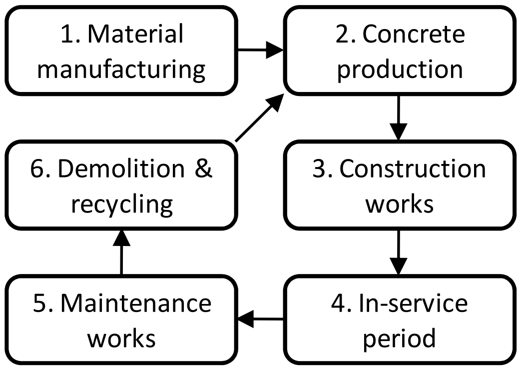


Figure 2 Material flow for construction (JCI, 2008)

### 2.3 Social impact

There is no common method for evaluating the social impact of concrete materials and structures. However, the user costs mentioned in Equation 1 are one way of measuring social impact. These user costs can include a variety of impacts that construction may have on the user of an infrastructure system, such as the delay caused by construction works, increase in accidents due to congestion in construction areas, the damage caused to vehicles due to deteriorated driving conditions, or the increase in gas consumption as users take detour routes to avoid congestion. The failure cost of the structure may also be included if the structure is of high importance or has a unique cultural value. Calculation of these costs requires the input of social data such as traffic flow, distribution, and so forth, as well as the value of users' time.

Another way of measuring the social cost may be the usage of recycled materials. As an example, the $CO_2$ emissions for producing recycled materials such as recycled aggregates may be greater than that for normal aggregates, depending on the regional level of industry. In this case, the benefit of using recycled materials cannot be clearly seen from an environmental analysis which focuses on emissions as a metric of environmental performance. However, the utilization of recycled materials has other important benefits such as reducing the amount of waste delivered to landfills. In some countries, land available for development or agriculture is scarce, so the creation of landfills takes up valuable space which could otherwise be put to better use. Therefore, reducing the disposal of materials to landfills can provide an important benefit to society. Since the value of recycled materials in concrete cannot be realized utilizing environmental metrics alone, it is proposed that recycled materials usage be classified as a social impact.

## 3. PROPOSAL OF TBL ASSESSMENT

### 3.1 Concept

Based upon the criteria discussed in the previous section, a simplified TBL assessment methodology is proposed. The term "simplified" is used to emphasize that the evaluation of economic, environmental, and social impacts is a complex task, so some assumptions must be made to provide a tool which can be applied easily yet still captures the essence of the problem.

This methodology is intended to be applied to concrete materials during the development process, in order to provide a means for assessing the sustainability of a material in addition to evaluation of its mechanical or durability performance. As such, the methodology is intended to focus on material costs and is comparative in nature, so many of the assumptions used to simplify the assessment process will be based upon the idea that similar costs between different materials can be disregarded.

### 3.2 Boundary conditions

The life cycle of a concrete material includes many phases, as was shown in Figure 2. However, during material development, the future application of a new material may not be clearly known, and the details regarding life cycle performance are difficult to determine. Therefore, for the simplified TBL assessment, only costs related to the material itself will be considered. While the choice of material may have an effect on the construction cost (such as construction period, casting methodology, curing, formwork, and so forth), these are indirect costs and not as easy to determine, so the costs assessed here will focus only on the material aspect.

### 3.3 Simplified TBL cost

The simplified TBL cost $C_{TBL}$ of the concrete material is calculated per Equation 2:

(2)

Where $C_{ECN}$ is the economic cost, $C_{ENV}$ is the environmental cost, and $C_{SOC}$ is the social cost.

### 3.4 Economic cost

The agency costs related to the concrete life cycle were discussed in Section 2.1. While the initial cost typically includes the work for design and construction, in this TBL assessment these costs will be ignored and the initial cost will be determined purely by the initial cost of materials.

The economic cost of the material $C_{ECN}$ is the initial cost of materials. The initial material cost can be calculated by multiplying the cost of each component by the mix proportions.

### 3.5 Environmental cost

The Intergovernmental Panel on Climate Change (IPCC) stated in 2007 that efforts to mitigate GHG emissions in the near future can have long-term benefits for reducing the effects of climate change (IPCC, 2007). As a result, it is important to focus on reduction of $CO_2$ emissions as the most critical environmental impact indicator. Therefore, the environmental cost for TBL assessment will be determined solely based on the cost of $CO_2$ emissions related to the concrete material itself.

The environmental cost $C_{ENV}$ is the cost of $CO_2$ emissions generated by the production of each of the components in the concrete material. The initial $CO_2$ cost is calculated as the total $CO_2$ emissions of concrete multiplied by the value of $CO_2$. The $CO_2$ emissions for concrete can be obtained by multiplying the life cycle inventory values by the mix proportions.

### 3.6 Social cost

The users costs discussed in Section 2.3 cannot be calculated without detailed information regarding the location of construction and the local traffic conditions and transportation pathways. While some research works have found that the user costs related to construction exceed the agency costs significantly, this is difficult to determine for a material during development. Due to the site-dependent variability related to calculating user costs, they will be disregarded for the TBL assessment.

The value of recycled materials, however, can be determined quite simply. When using waste or recycled materials in concrete, the amount of material being disposed to landfills is reduced. Since there is a disposal cost related to this process, utilizing greater amounts of recycled materials realizes a cost savings. In this TBL assessment, the use of recycled materials is a subsidized cost; that is, concretes which do not contain waste or recycled materials receive no penalty, but the usage of these materials allows for a discount in the final TBL cost, and is determined by the disposal cost savings.

The social cost $C_{SOC}$ is calculated as the cost of disposal of recycled materials utilized in the concrete, and can be determined by multiplying the cost of disposing the recycled materials by the volume of materials utilized in the concrete.

## 4. TRIAL CALCULATION

### 4.1 Concrete materials

In order to test the applicability of the proposed simplified TBL assessment, three different concrete materials will be evaluated. The first material (NC) is a plain concrete with a water-binder ratio of 0.4 and contains no recycled materials. The second material (FA50-NG) uses a water-binder ratio of 0.3, but replaces half the ordinary Portland cement with Grade 2 fly ash, an industrial waste by-product. The third material (FA50-RG) replaces half the Portland cement with fly ash, and also replaces all the normal aggregate with recycled aggregates. Complete mix proportions are given in Table 1.

Table 1 Concrete mix proportions

| | NC | FA50-NG | FA50-RG |
|---|---|---|---|
| Water-binder | 0.4 | 0.3 | 0.3 |
| Fly ash-binder | - | 0.5 | 0.5 |
| | kg/$m^3$ concrete | | |
| Water | 179 | 226 | 226 |
| Cement | 448 | 377 | 377 |
| Fly ash | - | 377 | 377 |
| Sand | 667 | 603 | 603 |
| Normal agg. | 986 | 416 | - |
| Recycled agg. | - | - | 373 |

### 4.2 Material costs

The material costs of the concrete components are given in Table 2. These costs were obtained from a catalog of material costs in Japan. Suppliers typically provide costs per cubic meter or per ton, so these values were converted to cost per kilogram. In the case of fly ash, the cost may vary greatly because the market for fly ash is not as open as other materials, such as Portland cement. Therefore, a private company was contacted and the cost of fly ash estimated based on their interview response. The cost for recycled aggregates was estimated from the price of recycled crushed stone used in road beds.

Table 2 Material costs (Sekisan-shiryou, 2008)

| | yen/$m^3$ | yen/ton | yen/kg |
|---|---|---|---|
| Water | 150* | - | 0.15 |
| Cement | - | 9600 | 9.60 |
| Fly ash | - | 4000** | 4.00 |
| Sand | 4050 | - | 1.55 |
| Normal agg. | 3600 | - | 1.33 |
| Recycled agg. | 1500 | - | 0.62 |

* Tokyo Metropolitan Bureau Waterworks

** Private company estimate

### 4.3 $CO_2$ inventory and cost

Table 3 gives the $CO_2$ emissions for the concrete components based on Japanese industry conditions. The cost of $CO_2$ is set at 2115 yen/ton (Kendall, 2004). This value was selected from research on the environmental cost of the direct and indirect impacts of $CO_2$, and converted from US dollars.

Table 3 $CO_2$ inventory (JCI, 2008)

| | kg $CO_2$/ton | kg $CO_2$/kg |
|---|---|---|
| Cement | 765.5 | 0.7655 |
| Fly ash | 17.9 | 0.0179 |
| Sand | 3.4 | 0.0034 |
| Normal agg. | 2.8 | 0.0028 |
| Recycled agg. | 2.8 | 0.0028 |

### 4.4 Disposal costs

The cost of $CO_2$ and the disposal cost for recycled and waste materials are given in Table 4. These values are based on the disposal rates for the Yokohama area.

Table 4 Disposal costs (Sekisan-shiryou, 2008)

| | yen/ton | yen/kg |
|---|---|---|
| Construction waste | 13000 | 13.00 |
| Fly ash | 15500 | 15.50 |

### 4.5 Calculation results

Following the calculation procedure as outlined in Section 3, the simplified TBL cost $C_{TBL}$ was calculated for each of the concrete materials. The results are given in Table 5.

Table 5 Calculation results

| | NC | FA50-NG | FA50-RG |
|---|---|---|---|
| | yen/$m^3$ concrete | | |
| $C_{ECN}$ | 6669 | 6646 | 6323 |
| $C_{ENV}$ | 736 | 631 | 631 |
| $C_{SOC}$ | 0 | 5844 | 10693 |
| $C_{TBL}$ | 7405 | 1433 | -3739 |

### 4.6 Discussion

A comparison of the calculated TBL cost for the three concrete materials is shown in Figure 3. From this figure, it can be seen that the NC mixture has the highest cost and the FA50-RG mixture has the lowest cost. The TBL cost is a representation of the cost to society for the concrete mixture, so the negative value of the FA50-RG mixture means that this material serves a benefit to society, whereas the FA50-NG mixture has a low cost to society and the NC mixture has a high cost to society.

The low TBL cost for the two fly ash mixtures is primarily driven by the social cost – the reduction of waste and recycled materials disposed at landfills.

The cost of disposal is much higher than most of the other costs, so based on this calculation method utilizing large amounts of waste and recycled materials can significantly reduce the TBL cost.

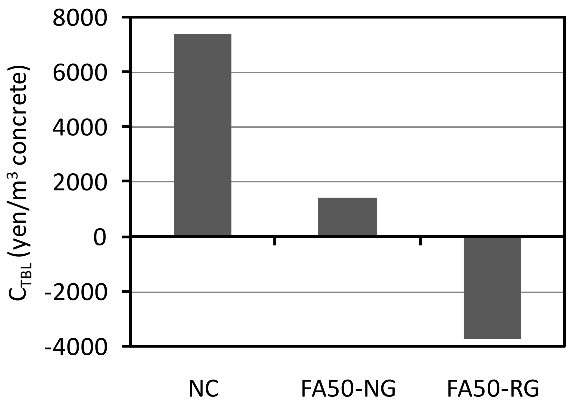


Figure 3 Triple bottom line cost

The economic cost – the cost of materials – is similar between the three mixtures, and the environmental cost is slightly lower for the two fly ash mixtures. This result is slightly misleading, as the environmental benefit of replacing cement with fly ash can be clearly seen in the difference in emissions between the two materials (Table 3). However, the concrete mixtures compared in this case do not share the same water-binder ratio, so there are more binder materials in the fly ash mixtures. Careful mix design is necessary to reduce the amount of cement as much as possible in order to achieve the greater $CO_2$ emissions reductions possible, but the mechanical behavior must also be considered in this case.

In addition, the cost of fly ash is much more variable than other concrete-making materials, so fluctuations in the fly ash cost could affect the different costs. Also, the value of $CO_2$ may increase in the future as more countries join in carbon trading and the impact of climate change becomes more severe, so the environmental cost of materials with high $CO_2$ emissions could grow higher.

## 5. FURTHER RESEARCH

The simplified TBL assessment as proposed in Section 3 is intended to be an indicator of the sustainability of a given concrete mixture. However, as proposed, the assessment methodology is independent of the mechanical behavior of the concrete. In order to integrate the TBL assessment with the mechanical behavior, a simplified life cycle model should be utilized. Since durability-based design is an important part of sustainable practice, the life cycle should be driven by durability factors, such as environmental deterioration (chloride penetration, carbonation, freeze-thaw, etc.) or mechanical fatigue. Once a life cycle model is selected, a maintenance cycle can be selected based upon the design conditions. As shown in Figure 4, durable materials require less maintenance operations, so the maintenance cost could be reduced in the TBL assessment. Materials with lower durability could be repaired when the limit of maintenance is reached, which increases the number of repairs and thus costs.

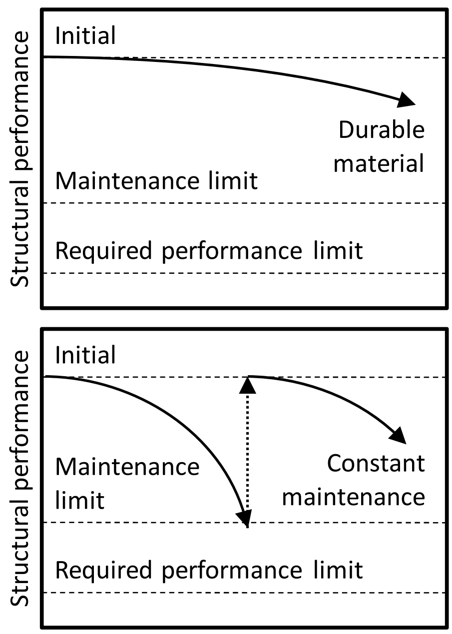


Figure 4 Maintenance strategies (Yokota et al., 2008)

By considering the costs of repair and

maintenance under deterioration conditions, the durability of a material can be coupled with the TBL cost to provide more comprehensive assessment of a concrete material over its life cycle.

## 6. CONCLUSION

In this paper, a simplified TBL assessment method was proposed for evaluating the sustainability of concrete materials during the development process. The TBL criteria – economic, environmental, and social – for a concrete material were proposed as the costs of the material, the cost of $CO_2$ emissions related to the material's components, and the savings realized by utilizing waste and recycled materials instead of disposing them.

Upon applying the methodology, it was found that a clear difference in TBL cost could be seen between three different concrete mixtures. The normal concrete mixture had the highest TBL cost due to the lack of recycled materials. The concrete mixture containing fly ash could significantly reduce the TBL cost compared to the normal concrete mixture, and the mixture containing fly ash and recycled aggregates could provide a social benefit due to the utilization of large amounts of recycled materials. The social cost – proposed as the usage of recycled materials – was found to be the primary factor in reducing the TBL cost. The environmental cost was similar between the different mixtures, but could be attributed to the difference in water-binder ratio between the normal concrete and fly ash concrete mixtures. These results are dependent upon the values of the materials utilized in the concrete, as well as the value of $CO_2$, so future fluctuations in these prices could significantly affect how the sustainable value of concrete materials is estimated.

While the proposed simplified TBL assessment may be useful for guiding the development of concrete materials towards those with sustainable value, it is necessary to combine the assessment method with durability performance indicators and develop a more comprehensive method which includes life cycle costs such as maintenance and repair. By accounting for the durability performance of a material in addition to its TBL cost, the proposed methodology could provide a better picture of the sustainability of concrete materials during the development process.

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