Efficiency of ultra-high-performance concrete applications on bridge construction

Duc Binh Tran and Van Tan Tran

Faculty of Construction Economics and Management, National University of Civil Engineering, 55 Giai Phong Road, Hanoi, Vietnam

E-mail: binhtd@nuce.edu.vn, tantv@nuce.edu.vn

Abstract. Ultra-High-Performance Concrete (UHPC) is a new building material with many mechanical and technical features that are outstanding comparing with traditional concrete (Normal Concrete-NC). This has been proved by many studies in the world but mainly on technical point of view, and only a few researches have been mentioned the economic-technical efficiency of this new material. This study compared two alternatives of bridge design and execution, one using the UHPC girders and another using the NC girders, the case study of An Thuong Bridge project in Hung Yen city, Vietnam. The economic-technical efficiency of UHPC is considered in many aspects such as technical, economic, environmental and social aspects. Four research methods were used to assess the efficiencies of UHPC, the method using integrated criterion, estimation method, life-cycle cost, and life-cycle assessment method. Through expert surveys and analysis of each alternative design, the final result shows that using UHPC is more efficient than using NC. Indeed, the alternative using UHPC has a lower cost and less environmental impact than the NC alternative. However, these conclusions are only true in the case An Thuong Bridge project. For the other cases, the replacement of NC by UHPC should be considered according to particular situations before implementing it. This research is useful for bridge construction managers, construction material production enterprises, bridge construction investors, etc.

1. Introduction

Ultra-High-Performance Concrete (UHPC) is a new construction material with a different composition in comparison to Normal Concrete (NC), known as traditional concrete. UHPC has been developed and applied to construction in many countries such as France, Germany, the United State of America, Canada, etc since the early 90s of the twentieth century. It was considered a landmark product in the development process of construction technology in general and concrete technology in particular. This is an advanced material with brilliant and remarkable features comparing with NC [1]: higher compressive strength, higher tensile strength and higher reliability [2]. UHPC is a mixed material of sand, cement, silica fume, superplasticizer and discontinuous reinforced steel fiber with compressive strength higher than 150 MPa [3]. The usage of steel fibers increases the tensile strength of UHPC and paves the way to exploit the outstanding features of this material. Therefore, using UHPC in the construction structure instead of traditional material such as NC, prestressed concrete, steel, etc is still a controversial problem.

Many researchers focus on mechanical features of UHPC and all of them have proved the superiority of UHPC over NC. However, it is essential to specifically assess the economic–technical
efficiency that UHPC brings about when it is practically applied. There are fewer researches about the efficiency of UHPC than those about its technical features. Nowadays, there are only a few researches about the economic–technical efficiency of UHPC [4, 5, 6, 7]. These researches just focus on comparing several individual efficiency indicators between UHPC and NC but lack of general comparison. In Vietnam, UHPC is still in testing progress, thus researches usually focus on technical features of UHPC. Moreover, the application of a new construction material depends on a particular situation and context, thus it is important to have a suitable assessment method.

This research is one of the topics belonging to a Science and Technology Program at ministry level “Study on the application of Ultra-High-Performance Concrete (UHPC) on producing small and medium bridges”, launched by the National University of Civil Engineering (NUCE). This paper focuses on the economic-technical efficiency applying UHPC on producing small and medium bridges in Vietnam, the case study of An Thuong Bridge, in Hung Yen city. The final result shows that the bridge using the UHPC girders has a higher economic – technical efficiency than the NC girders.

2. Research methods
To assess the economic-technical efficiency using UHPC on bridge construction, two alternatives of bridge construction, one using the UHPC girders and another using NC were compared. Numerous research methods were used in this work.

2.1. Method using integrated criterion
This method allows integrating all the indicators with different units of measurement (currencies, objects...) into one criterion without measurement unit and ranking alternatives for selection. The integrated criterion considers also the importance of each individual indicator through weighting it [8, 9, 10, 11].

Suppose that there are \( n \) alternatives to compare, and there are \( m \) indicators in the calculation (each indicator represents a factor affecting the decision). The integrated criterion of each alternative is the objective function and can be chosen to approach Min or Max value according to particular situations. The function is as follow:

\[
V_j = \sum_{i=1}^{m} P_{ij} \times W_i
\]

where \( V_j \) is the integrated criterion of the alternative \( j \);
\( W_i \) is the weight which presents the importance of indicator \( i \), obtained from expert opinions;
\( P_{ij} \) is the value of indicator \( i \) of alternative \( j \) after eliminating the measurement unit, calculated as the function below:

\[
P_{ij} = \frac{C_{ij}}{\sum_{j=1}^{n} C_{ij}}
\]

where \( C_{ij} \) is the real value of indicator \( i \) of alternative \( j \). In case indicator \( i \) does not have a measurement unit (known as the qualitative indicator), then expert opinions are taken into account. In case indicator \( i \) has a variation direction opposite to the direction of the selected objective function, then the inverse value of it must be taken to remove the unit.

After calculating the integrated criteria of every alternative as in equation (1), the alternatives are then compared and ranked towards the direction of the selected objective function.

2.2. Estimation method
For the indicators in the comparison between using new construction material and traditional material, there are many indicators that require an estimation to determine their value, for instance, construction investment cost, maintenance cost, labor work... To implement this method, the research team uses F1 estimation software, along with the guidance documents of the Ministry of Construction, the Ministry of Transport ... in the construction estimate [12, 13, 14, 15].
2.3. Life Cycle Cost method
Life Cycle Cost (LCC) reflects the cost incurring throughout the life cycle of the product, commencing from the manufacturing phase to the consuming phase, which is calculated as below:

$$\text{LCC} = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$$

where $n$ is the number of the life cycle of the product including manufacturing and consuming phases;
$C_t$ is the cost occurring in year $t$ of the life cycle;
$i$ is the discount rate determined by the interest rate of the capital market.

LCC can be used for not only directly comparing the application of new and traditional material but also used in indicators system to compare by the integrated criterion.

2.4. Life Cycle Assessment method
Life Cycle Assessment (LCA) is used to calculate the indicators which impact the environment \([16, 17]\). Here, Cumulative Energy Demand CED (MJ eq Solar) and Global Warming Potential GWP (kg CO$_2$ eq) are used for both UHPC and NC alternatives. Bridge construction life assessment is processed by OpenLCA software and the Ecoinvent database. The environmental impact of 1m$^3$ UHPC and 1m$^3$ NC is calculated firstly by summarizing the environment impact data of each component of UHPC and NC. This data are collected from the Ecoinvent database. Afterward, the environmental impact of these two alternatives, girder only, is determined by multiplying with the weight of each girder. The environmental impact of the whole bridge is the sum of the environmental impact of the components that build the bridge.

2.5. Expert survey method
This method is utilized to collect opinions from experts to examine the compatibility of the suggested assessment indicators and to decide the weight of each indicator as well as to determine the value of qualitative indicators. Survey objects are experts in construction material, architecture, bridge construction management. The content of the questionnaire consists of three parts:

Part 1: The information of the participants. The information about the number of years of experience and responsibilities of those experts in the construction field is collected.

Part 2: The knowledge about UHPC and bridge construction. The research team asks the participants how they know about UHPC as well as bridge construction, bridge maintenance, and bridge management. This information is to evaluate the reliability of experts’ responses.

Part 3: Indicators system for evaluation, comparison between alternatives using UHPC and NC in design, execution, and maintenance of small and medium bridges. The questions in this part require the experts to mark the assessment indicators and their weights in comparing the application of UHPC with that of NC. In this part, qualitative indicators in the comparison model are marked by the experts, either.

3. Research results

3.1. Assessment model of economic–technical efficiency of UHPC on bridge construction
A model to compare UHPC and NC use on bridge construction is built. The objective function to compare is an integrated criterion. There are 2 alternatives that satisfy the requirements of building functions (one using UHPC girders and another using NC girders). 35 indicators are suggested in this model, divided into 4 groups as in Table 1.
Table 1. Evaluation indicator groups on economic–technical efficiency.

| Group of indicators | Targets of the alternative                                                                 | Number of indicators |
|---------------------|-------------------------------------------------------------------------------------------|---------------------|
| Technical group     | Meet the design standards as well as industry standards.                                   | 16                  |
| Economic group      | Minimize costs and/or bring positive revenue to the project.                               | 7                   |
| Environmental group | Meet the requirements of relevant laws and regulations and minimize the impacts (and/or maximize the beneficial impacts) on the project’s soil, air, and water environment. | 8                   |
| Social group        | Meet the requirements of relevant laws and regulations and minimize the harms (and/or maximize the beneficial impacts) on the cultural environment, population, heritage, archeology, health and aesthetic. | 4                   |

The details of the indicators are presented in the results of the model applied on An Thuong Bridge.

3.2. Results of expert survey

Among 200 questionnaires sent away, there are 160 responses collected from experts in construction, corresponding with an 80% rate of response. There are 6 invalid responses due to the lack of answers or disunion answers. Thus, 154 survey responses were used to analyze.

All experts participated in this survey work in bridge design, execution and construction management. 44.16% of them have 5-to-15-year of experience and 14.94% of them have more than 15 years of experience. This assures the reliability of their response.

95.45% of experts agree with the suggested economic–technical indicators system. The experts mark the level of importance of the indicator from 1 to 5 according to the Likert scale and the weight of each indicator is the average of the scores of 154 experts.

3.3. Comparison between the applications of UHPC and NC on An Thuong Bridge

3.3.1. Introduction of two building alternatives An Thuong Bridge

An Thuong Bridge crosses irrigation channel in An Tao District, Hung Yen City, Hung Yen Province, Vietnam and is chosen to test the application of UHPC. This newly built bridge replaces the old An Tao Bridge, which threatens the safety of people and vehicles. The investor is Ngoc Khanh Electric Wire & Cable Co., Ltd, design consultancy is Tan Phong Consulting and Construction Joint Stock Company. NUCE is responsible for designing and manufacturing three girders using UHPC.

To assess the efficiency of UHPC, 2 alternatives for construction are proposed: one using the UHPC girders system and another using the NC girders system.

The bridge that uses UHPC girders is designed to be 31.1 m long with span is 21 m in length. The bridge is 5 m wide, consists of 3 main UHPC girders with section I, which is 0.72 m high and 1.75 m apart. (Figure 1). The bridge deck is 19 cm-thick made from reinforced concrete, is supported by a permanent UHPC framework system, 35 mm-thick. Two abutments are made of reinforced concrete, reinforced concrete piles 30×30 cm with 14 piles per abutment.
Figure 1. Cross-section of An Thuong Bridge, alternative using UHPC.

The other alternative using NC is designed to be 31.1 m long with span is 21 m in length. The bridge is 5 m wide, consists of 5 main box girders using NC, which is 0.8 m high (Figure 2). The bridge deck is made of reinforced concrete with 15 cm thickness. The abutments and piles design is the same as the UHPC alternative but the number of piles per abutment is 20.

Figure 2. Cross-section of An Thuong Bridge, alternative using NC.

The main difference between the two alternatives is the girders system, bridge deck and the number of piles. Besides, An Thuong Bridge project also carries out other activities such as the execution of pathways, including roadbed and road surface, abutments… These activities are the same in two alternatives.
3.3.2. UHPC concrete mixture.
To evaluate the economic-technical efficiency of UHPC in the An Thuong Bridge project, the research team compared the alternative using UHPC and the other using NC. UHPC in this project was researched and manufactured by Faculty of Building Materials, NUCE while NC was traditional concrete M300. The composition of these two materials is given in Table 2.

Table 2. Composition of UHPC and NC.

| N°  | Composition       | Weight (kg/m³) |
|-----|------------------|----------------|
|     |                   | 1 m³ UHPC      | 1 m³ NC       |
| 1   | Water            | 160.6          | 168.0         |
| 2   | Cement           | 771.0          | 370.0         |
| 3   | Sand             | 1,101.4        | 800.0         |
| 4   | Crushed stone    | -              | 1,080.0       |
| 5   | Superplasticizer | 40.4           | 3.7           |
| 6   | Steel fiber      | 157.0          | -             |
| 7   | Silica fume      | 110.1          | -             |
| 8   | Fly ash          | 220.3          | -             |
| 9   | Prestressed cable| 270.7          | 70.8          |
| 10  | Reinforced steel | 78.1           | 218.3         |

3.3.3. Determination of indicators’ value and comparison.
There are 35 indicators divided into 4 groups as suggested. Quantitative indicators are determined by the above alternatives, while qualitative indicators are quantified by the experts’ opinions.
With respect to the economic group, based on the composition and production organization method, 1 m³ UHPC is estimated to cost $816.44 and 1 m³ NC is estimated to cost $169.58. Based on the design of each alternative and recent price, the indicators in the economic group are calculated as Table 3.

Table 3. Economic indicators of two alternatives.

| N°  | Indicator (i)                              | Unit      | Alternative using UHPC | Alternative using NC | Weight (%) |
|-----|-------------------------------------------|-----------|------------------------|----------------------|------------|
| 1   | Bridge construction investment costs      | USD       | 195,204.45             | 219,064.66           | 3.245      |
| 2   | Investment cost for girders               | USD       | 27,135.85              | 38,887.48            | 3.010      |
| 3   | Bridge maintenance cost (for the whole life cycle, discounted to the present) | USD       | 42,235.85              | 45,022.98            | 2.962      |
| 4   | Financial life cycle cost of the bridge   | USD       | 237,432.63             | 264,087.64           | 2.908      |
| 5   | Investment cost per 1 m² bridge deck      | USD/m²    | 1,714.21               | 1,923.81             | 2.932      |
| 6   | Localization level                        | %         | 97.25                  | 100.00               | 2.826      |
| 7   | Laborwork per 1 m² bridge deck            | Daywork b | 41.927                 | 48.275               | 2.746      |

a Laborwork is equal to the number of workers multiplied by the number of workdays
b Daywork includes 8 working hours
Although the cost of 1m$^3$ UHPC is 5 times higher than that of 1m$^3$ NC, the cost of the UHPC girders system is still lower than the NC girders system. The reason is the outstanding tensile strength of UHPC. It reduces the required number of girders using UHPC. Similarly, the cost of bridge construction alternative using UHPC is smaller than that of alternative using NC due to the smaller number of girders, bearings, and piles. These advantages thank to the tensile strength of UHPC.

Bridge using UHPC also has an advantage in maintenance costs due to the sustainability of UHPC. This leads to the fact that the life cycle cost of the bridge using UHPC is relatively lower than that of the bridge using NC. This is the economic efficiency of applying UHPC on An Thuong Bridge.

The technical indicators group consists of quantitative and qualitative indicators. Quantitative indicators are determined based on data from each construction alternative design and execution as well as bridge construction standards (Table 4).

| N°  | Indicator (i)                  | Unit     | Alternative using UHPC | Alternative using NC | Weight (%) |
|-----|--------------------------------|----------|------------------------|----------------------|------------|
| 1   | Service life of girders        | year     | 100                    | 100                  | 3.303      |
| 2   | Service life of bridge         | year     | 100                    | 100                  | 3.250      |
| 3   | Weight of girders              | ton      | 32.977                 | 146.250              | 2.877      |
| 4   | Weight of bridge               | ton      | 1,002.348              | 1,212.828            | 2.743      |
| 5   | Girders casting time           | month    | 1.5                    | 2.5                  | 2.646      |
| 6   | Girders erection time          | month    | 0.25                   | 0.5                  | 2.606      |
| 7   | Total construction time        | month    | 5.0                    | 5.5                  | 2.879      |
| 8   | Bridge maintenance period      | year     | 30                     | 30                   | 2.863      |

Because An Thuong Bridge alternative only uses UHPC in the girders system, other components still use NC, thus when comparing the two alternatives, the girder service life is considered to be similar to bridge service life. In terms of qualitative indicators, their values are determined by collecting opinions from experts through surveys and then compare to alternative using NC.

| N°  | Indicator (i)                  | Unit (scale 1-5) | Alternative using UHPC | Alternative using NC | Weight (%) |
|-----|--------------------------------|------------------|------------------------|----------------------|------------|
| 1   | Span capability of girders      | point            | 3.861                  | 3                    | 3.266      |
| 2   | Navigational clearance         | point            | 3.681                  | 3                    | 2.874      |
| 3   | Simplicity in casting girders in term of the technical aspect | point | 2.444                  | 3                    | 2.792      |
| 4   | Simplicity in casting girders in term of the organizational aspect | point | 2.597                  | 3                    | 2.692      |
| 5   | Simplicity in erecting girders in term of the technical aspect | point | 3.097                  | 3                    | 2.692      |
| 6   | Simplicity in erecting girders in term of the organizational aspect | point | 3.083                  | 3                    | 2.641      |
| 7   | Simplicity in executing bridge in term of the technical aspect | point | 2.875                  | 3                    | 2.725      |
The alternative using NC is the base alternative, therefore all indicators in this alternative are marked 3. These indicators in the alternative using UHPC are marked from 1 to 5 by the experts (from very bad to very good corresponding). According to survey results, experts suppose that comparing to the alternative using NC, the one using UHPC is simpler in terms of girder installation (both technical and organizational aspects), but more complicated in girder manufacture and whole bridge execution (Table 5).

When considering the environmental impact of UHPC and NC, the authors use the LCA indicators such as Cumulative energy demand CED (MJ eq Solar), Global warming potential GWP (kg CO\textsubscript{2} eq).

| N\textsuperscript{0} | Indicator (i) | Unit | Alternative using UHPC | Alternative using NC | Weight (%) |
|----------------|---------------|------|------------------------|----------------------|------------|
| 1              | CED of girder system | MJ eq Solar | 8.654 | 9.257 | 2.479 |
| 2              | CED of bridge | MJ eq Solar | 34.434 | 40.23 | 2.557 |
| 3              | GWP of girder system | Kg CO\textsubscript{2} Eq | 28,526.87 | 51,253.90 | 2.509 |
| 4              | GWP of bridge | Kg CO\textsubscript{2} Eq | 140,754.63 | 190,303.73 | 2.558 |
| 5              | GWP of girder system, erection included | Kg CO\textsubscript{2} Eq | 30,611.795 | 54,249.840 | 2.847 |
| 6              | GWP of bridge, execution included | Kg CO\textsubscript{2} Eq | 171,772.63 | 224,782.59 | 2.960 |
| 7              | GWP of bridge operation | Kg CO\textsubscript{2} Eq | 413,753.48 | 413,777.79 | 2.902 |
| 8              | GWP of bridge throughout the life cycle | Kg CO\textsubscript{2} Eq | 585,526.11 | 638,560.39 | 2.871 |

Based on the mixture composition, the production of 1m\textsuperscript{3} UHPC emits 2,647.63 kg CO\textsubscript{2} eq (measured by GWP 100a) and consumes 0.8195 MJ eq solar energy (measured by CED). These two indicators of 1m\textsuperscript{3} NC are 980 kg CO\textsubscript{2} eq and 0.177 MJ eq solar respectively. It can be seen that the environmental impact of UHPC is much higher than that of NC because UHPC uses concentrated material with high content. However, in the situation of An Thuong Bridge project, the alternative using the UHPC girders is friendlier to the environment due to the smaller amount of material used in a general comparison (Table 6).

When studying the social efficiency of UHPC, the qualitative indicator “Aesthetic of girders and bridge” is proposed. Because UHPC has superior features over NC (tensile strength and compressive strength), components using UHPC will have a smaller required section under the same load. Therefore, the application of UHPC on bridge construction, especially girders, makes the high and the wide of UHPC girders shorter than that of NC girders. Besides, the production of UHPC components is more complicated than NC because UHPC uses fine aggregate which is easy to be released in the air. Moreover, small diameter steel fibers easily injure workers during the manufacturing process, thus, two qualitative indicators to the social group: “Ability to reduce the impact on the health of workers” and “Ability to reduce the requirement of protection equipment for workers” are proposed. The alternative using NC is still the base alternative. The results are given in
Table 7.

| No  | Indicator (i)                                | Unit (Scale 1-5) | Alternative using UHPC | Alternative using NC | Weight (%) |
|-----|---------------------------------------------|------------------|------------------------|----------------------|------------|
| 1   | Aesthetic of girders                         | Point            | 3.764                  | 3                    | 2.952      |
| 2   | Aesthetic of bridge                          | Point            | 3.653                  | 3                    | 3.151      |
| 3   | Ability to reduce the impact on the health of workers | Point            | 2.931                  | 3                    | 3.030      |
| 4   | Ability to reduce the requirement of protection equipment for workers | Point            | 2.972                  | 3                    | 3.054      |

According to experts, alternative using UHPC improves the aesthetic of girder and the whole bridge when compared with NC, but it also influences the health of workers and requires more labor protection equipment.

3.3.4. Calculation of the integrated criterion

The variation direction of the objective function is chosen as small as possible. The values of the indicators (calculated in the tables above) are removed their measurement unit as in equation 2. For the indicators whose the variation direction is inversely opposite to the variation direction of the selected objective function, their values will be inversely calculated. After this step, the values of the indicators after eliminating the measurement unit are obtained. The integrated criterion is calculated by the sum of these values multiplied by the weight of each corresponding indicator as in equation 1. The order of calculations is the same for both 2 alternatives.

The integrated criterion of the alternative using UHPC is 45.734 scores and that of the alternative using NC is 54.255 scores. That means the alternative using the UHPC girders system has a higher economic–technical efficiency than the one using the NC girders system in An Thuong Bridge project.

4. Discussion

In the case study of An Thuong Bridge project, the initial investment cost of 1m³ UHPC is 4.8 times higher than that of 1m³ NC, and 1m³ UHPC impacts on the environment 2.7 times more than 1m³ NC. These results are quite similar to the existing researches. However, the efficiency of UHPC lies in its superior mechanical and technical features which reduce the quantities of construction works. Particular efficiencies are as follow:

- The integrated criterion shows that UHPC bridge alternative is more beneficial than NC bridge alternative;
- The construction investment cost of girders system using UHPC is about 30.2% lower than that of NC;
- The life cycle cost of the bridge using UHPC girders system is about 10.1% lower than that of NC;
- The environmental impact of girders system using UHPC is much smaller than that of NC, about 46.3%;
- The environmental impact of the bridge using the UHPC girders system is about 8.3% smaller than that of NC.

The above results may be useful for bridge construction managers, construction material production enterprises, bridge construction investors, etc. However, the proportion of UHPC used in
this bridge project is still not high, only applied for the girders system. For future projects, the more UHPC application will probably bring more efficiency. Besides, there are no regulations or data on the UHPC project in Vietnam, so some criteria in this paper are considered the same for the two alternatives, such as “Service life of girders” and “Bridge maintenance period”.

5. Conclusions
UHPC shows superiority through mechanical features and durability compared to NC, and the economic-technical efficiency of UHPC is also higher than that of NC in An Thuong Bridge project. The alternative using UHPC is more economical and has a lower environmental impact than the alternative using NC, both for girders system and whole bridge. The calculation of integrated criterion allows a comprehensive comparison between UHPC and NC in many aspects. Based on the research results, it can be observed that the development and application of UHPC on bridge construction in particular, and construction in general, should be encouraged in the future. However, the replacement of NC by UHPC should be considered according to particular situations before implementing because UHPC is not always better than NC. In general, the alternative using UHPC is only more efficient than another using NC when it helps reduce significantly the quantities of construction works thanks to the superior features of UHPC.

Acknowledgements
In this section, we would like to express our sincere thanks to all the members of the research team who have always accompanied us throughout the study. In addition, we would also like to thank the experts of Transport Engineering Design Incorporated (TEDI) Vietnam, who were very enthusiastic to participate in the survey to help us get the valuable data for analysis. And finally, we would like to thank our colleagues, lecturers of the Faculty of Building Materials, Faculty of Bridge and Roads, NUCE, for their enthusiastic support, their suggestions are really significant for this study.

References
[1] Stengel T and Schießl P 2014 Life cycle assessment (LCA) of ultra high performance concrete (UHPC) structures Eco-Efficient Construction and Building Materials: Life Cycle Assessment (LCA), Eco-Labelling and Case Studies (Woodhead Publishing Limited) chapter 22 pp 528-564 DOI: 10.1533/9780857097729.3.528
[2] Russell G H and Graybeal B A 2013 Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community (The Federal Highway Administration) Report No: FHWA-HRT-13-060
[3] Alkaysi M, El-Tawil S, Liu Z and Hansen W 2016 Effects of Silica Powder and Cement Type on Durability of Ultra-High Performance Concrete (UHPC) Cement and Concrete Composites Journal 66 pp 47-56 DOI: 10.21838/uhpc.2016.87
[4] Lee C, Kim K and Choi S 2013 Application of Ultra-High Performance Concrete to Pedestrian Cable-stayed Bridge Journal of Engineering Science and Technology 8(3) pp 296–305
[5] Ultra High Performance Concrete – Pathway to Commercialization 1/2011 Ultra High Performance Concrete (UHPC) Workshop (New York: Department of Homeland Security - Science and Technology)
[6] Maher K and George M 2009 Application of Ultra-High Performance Concrete to Bridge Girders Final Reports & Technical Briefs from Mid-America Transportation Center (University of Nebraska-Lincoln) Report No: SPR-P1(08)/P310
[7] Stengel T and Schießl P 2009 Life cycle assessment of UHPC bridge constructions: Sherbrooke Footbridge, Kassel Gärtnerplatz Footbridge and Wapello Road Bridge Architecture Civil Engineering Environment Journal (The Silesian University of Technology) 1 pp 109-118
[8] Nguyen V C 1996 Rationale for investment economics and construction design (Vietnam: Graduate bookcase National University of Civil Engineering)
[9] Nguyen V C 2001 Investment economics Vol 1 (Vietnam: Statistical Publishing House)
[10] Nguyen V C 2001 *Investment economics* Vol 2 (Vietnam: Statistical Publishing House)
[11] Nguyen V C 2003 *Economics of construction investment* (Vietnam: Construction Publishing House)
[12] Ministry of Transport 2014 Decision No. 3409/QD-BGTVT dated September 8, 2014 of the Minister of Transport on promulgation the norm of regular road maintenance (in Vietnamese)
[13] Ministry of Construction 2016 Circular No. 06/2016/TT-BXD dated March 10, 2016 of the Minister of Construction on guidelines for determination and management of construction investment costs (in Vietnamese)
[14] Government 2010 Decree No. 114/2010/ND-CP dated December 6, 2010 of the Government on maintenance of construction works (in Vietnamese)
[15] Government 2015 Decree No. 32/2015/ND-CP dated March 25, 2015 of the Government on management of construction investment costs (in Vietnamese)
[16] Bakhoun E S and Brown D C 2012 Developed Sustainable Scoring System for Structural Materials Evaluation *Journal of Construction Engineering and Management* 138(1) pp 110-119 DOI:10.1061/(ASCE)CO.1943-7862.0000412
[17] Bakhoun E S and Brown D C 2015 An automated decision support system for sustainable selection of structural materials *International Journal of Sustainable Engineering* 8(2) pp 80-92 DOI: 10.1080/19397038.2014.906513