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# Cost-Benefit Analysis of Vibrated Concrete and Self–Compacting Concrete Containing Recycled Aggregates and Natural Pozzolana

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## ABSTRACT

The use of vibrated concrete (VC) and self–compacting concrete (SCC) with adequate strength, cost-effectiveness, and sustainability is required to meet the current requirements in the concrete industry. Therefore, the development of an economical and durable concrete while comparing the life cycle cost of the structures, which includes the initial cost of the material, labor, and the cost of maintenance and repair, is of prime importance. The prevailing cost of materials and labor from the local market was collected to calculate the total cost of the concrete mixes. Both vibrated concrete and self–compacting concrete mixes containing conventional materials as well as locally and regionally available materials were developed, and a decision matrix was used for the cost-benefit analysis. The cost analysis of different mixes showed the economic benefit of self–compacting concrete compared to vibrated concrete, and further confirmed the added advantage of incorporating volcanic ash (VA) and recycled coarse aggregates (RCA) for the economic development of concrete mixes.

**Keywords:** Decision matrix; Durability; Cementitious materials; Sustainable; Volcanic ash

## INTRODUCTION

The construction industry plays a major role in the economic development of Kuwait. The demand for new buildings and infrastructures is increasing every year due to the increase in population and formulation of new Government policies for superior infrastructural development. Figure 1 shows the share of the construction Industry in the GDP from 2004 to 2017 in Kuwait. The infrastructure construction was the third-largest market in the Kuwaiti construction industry in the last five years, with several mega projects worth more than USD 188 bn (Al-Fadala et al., 2019). In addition to cost-effectiveness, the appropriate use of sustainable materials is required to meet the demand of increased service life of these infrastructures.

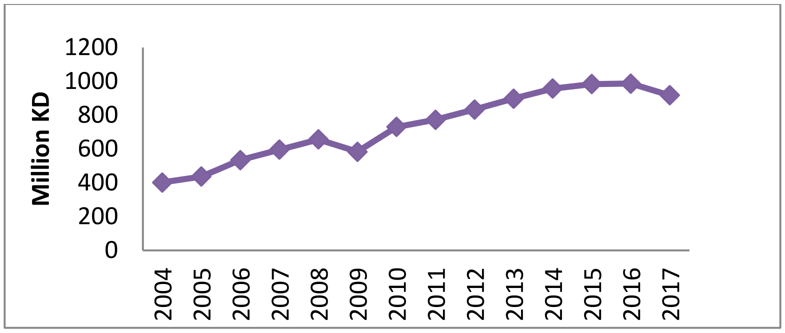


**Fig. 1.** Construction industry share in GDP.

Source: Statistical Bureau Kuwait, Annual Abstracts Statistic

In addition, building materials represent 47% of the industrial sector due to the large-scale construction activities in the country. Except sand, other raw materials required for the construction are imported from neighboring countries, causing an increase in the cost of construction due to higher transportation cost. Figure 2 shows the imports and exports of different types of building materials including cement, stone, aggregates, decorative stones, marbles, tiles, or similar materials. The necessity of using alternate materials as a replacement for cement is derived from the fact that the domestic cement production of 11 Mt/year could not meet the country's demand due to several mega projects in recent years. Hence, 3.65 million metric tons of cement are imported from Saudi Arabia and United Arab Emirates. Considering the impact of the construction industry on the environment and economy, the concept of sustainable construction requires revised strategies to implement the cost-effective green construction practices in future infrastructure and housing projects.

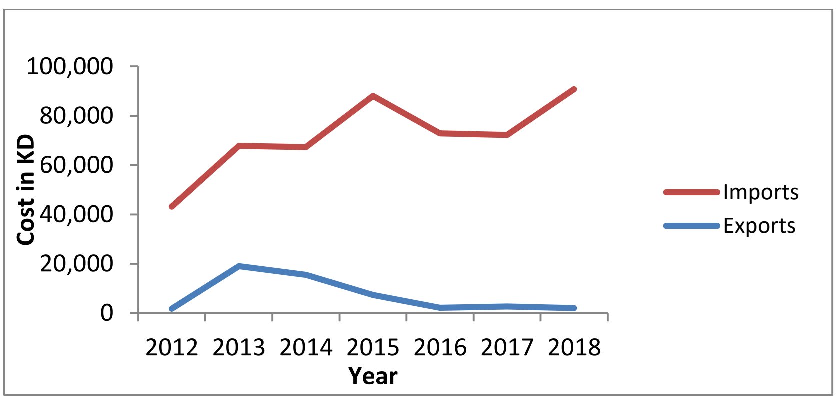


**Fig. 2.** Imports and exports of building materials**.**

Source: Statistical Bureau Kuwait, Foreign Trade Statistics

The Arabian Gulf region's high temperature, humidity and marine conditions provide an extremely aggressive environment for reinforced concrete structures. Hence, the concrete industry in Gulf countries faces the challenge of reduced life of concrete structures resulting in a large quantity of demolished wastes. Moreover, Kuwait is a country with limited natural resources, and it has become a requirement to find out alternate cementitious materials and other sources of aggregates for concrete construction. This issue can be addressed with the incorporation of regionally available and recyclable materials in construction. Even though many research studies have been conducted on the feasibility of using recycled aggregates, its use is not extensively practiced in small or big projects for concrete constructions. In addition, the use of self–compacting concrete (SCC) for housing and mega projects is considered as one of the sustainable and cost-effective construction practices in other countries. Therefore, promoting the production and use of SCC among ready-mix companies and local bodies is required to meet the construction boom in Kuwait.

Thus, the challenge before the engineering community is to achieve sustainable and cost-effective vibrated concrete (VC) and self–compacting concrete (SCC) with adequate strength for the construction of buildings and infrastructures.

Several studies have been reported about the strength and durability properties of VC and SCC with binary and ternary blends of fly ash, slag and silica fume (Gettu et al. 2002; Grdic et al. 2010; Kou Shi-Cong et al. 2011; Jawahar et al. 2013 a, b; Behera et al. 2014; Pereira-de-Oliveira et al. 2014; Celik et al. 2014). Also, a recent research study conducted at the author's institute had validated the potential of using regionally available volcanic ash as an alternative supplementary cementitious material in concrete (Al-Bahar et al. 2017; Al-Fadala et al. 2017). A similar study on the performance evaluation on the strength and durability of VC and SCC with sustainable materials such as volcanic ash and recycled coarse aggregates was carried out in the first stage of this study, and the details were reported earlier (Chakkamalayath et al. 2018; Chakkamalayath et al. 2020).

However, limited studies have been reported about the cost-benefit analysis of incorporating these sustainable materials in the development of VC and SCC, which is the prime requirement for the use of alternative materials and technology (Pai 2004; Jawahar et al. 2013b). Even though the initial material cost of SCC may be 10-15% higher than that of VC, depending on the strength class, it is estimated that SCC may result in up to 40% faster construction than using VC (Perssoiv 1998; Nocher 2001; Pai 2004). This is the most important criteria for the cost effectiveness in the construction industry, especially in the case of pre-fabricated construction of bridge elements. Furthermore, the modification in the viscosity, and flow properties of SCC can be achieved by the replacement of cement with higher volume of mineral admixtures resulting in an increase in paste volume, and subsequently reducing the cost of SCC (Murthy 2014).

The mixes selected for the cost comparison and analysis had shown good performance in terms of fresh and hardened properties, as reported in the first part of the study (Chakkamalayath et al. 2020). The cost of preparing and placing concrete for various constructions depends on the relative cost of different materials and the labor cost at the place of the construction. Hence, as a case study, the prevailing cost of materials and labor were collected from the Ready-mix companies in Kuwait and those details were used in the determination of the cost of the concrete mixes per cubic meter of concrete. Accordingly, the cost-benefit analysis of incorporating regionally available volcanic ash and locally available recycled aggregates was also evaluated and reported in this paper.

## Significance in the Development of Sustainable SCC

Compared to VC, SCC construction generally requires less time, and minimum labor resulting in cost-effective and faster construction (Bernabeu 2000, EFNARC Guidelines 2005). Hence, it is generally recommended for mega projects including skyscrapers and other infrastructural constructions. Another advantage of SCC construction is the improvement in the health and safety of workers due to the lack of vibration during placing of concrete. A case study of placing SCC in in a precast plant reported a reduction in time and labor of 20%, and 32% respectively, compared to a conventional mixture (Martin, 2002). Also, an average reduction of 30% in labor is generally considered during the placing of SCC, irrespective of the type of work. The flowability, passing ability, and the segregation resistance, which are considered as the three basic requirements for the acceptance of a SCC mix, can be achieved with the incorporation of appropriate type of chemical and mineral admixtures. This necessitates the use of locally and regionally available materials for making it further sustainable and economical.

One of the locally available materials that can be used for replacing normal aggregates is the recycled aggregates. Recycled aggregates are taking from demolished buildings, that are available because of the reduced life of concrete structures due to extreme weather and marine conditions in Kuwait. There is a significant increase in construction waste over the last few years and approximately, 1.6 million tons/year of construction and demolition wastes (C&D) are produced in Kuwait and are stored in four main C&D waste dumpsites with a total area of approximately 33 km$^2$ (Al-Fadala 2019). This highlights the necessity of using recycled aggregate in construction to meet the scarcity of aggregates as well as to reduce the adverse effect on the environment.

Similarly, the use of volcanic ash (VA) has to be promoted as it is regionally available in Saudi Arabia and Yemen, whereas other supplementary cementitious materials are imported from other countries such as China, South Korea, India, and Europe. Therefore, the use of VA results in reduction in transportation cost resulting in a net reduction in material cost. On the other hand, the cost of GGBS is higher than cement in Kuwait. The detailed study on the benefits of incorporating VA on the mechanical properties and microstructure of concrete is reported elsewhere (Al-Bahar et al. 2017; Al-Fadala et al. 2017).

Even though there are several technological advantages for SCC, its use is limited in normal housing construction in Kuwait due to the assumption of the higher initial cost, without considering the reduction in life cycle cost, and better performance. The economic benefit of SCC has to be evaluated to promote its use for mass housing to meet the increased housing demand and quality construction in Kuwait. Additionally, its use has to be promoted for infrastructure construction as the accelerated construction using SCC will result in cost effectiveness of mega structures. Therefore, an investigative study on the cost-benefit analysis of sustainable SCC in comparison with VC is reported in this paper.

## METHODOLGY

Vibrated concrete (VC) and self–compacting concrete (SCC) were prepared with the conventional materials as well as with the incorporation of volcanic ash (VA), ground granulated blast furnace slag (GGBS) and recycled coarse aggregates (RCA). The cost analysis of different concrete mixes containing the alternate sustainable materials was carried out based on the usual cost of materials and labor in Kuwait. The cost comparison was prepared based on the total cost, which includes the capital and operating costs. Capital costs are fixed one-time expenses and are therefore independent of the level of output, whereas operating costs are variable, and dependent on the level of output and is considered as the total cost needed in daily operations. The use of a decision matrix to evaluate the cost-effectiveness of different mixes and the method to achieve an optimum mix is presented in this paper.

### Materials

The raw materials including ordinary Portland cement (OPC), aggregates, polycarboxylate ether (PCE)-based superplasticizer (SP), and viscosity modifying agent (VMA) required for the preparation of VC and SCC were obtained from the local market. The dosage of SP and VMA was determined using the Marsh cone and mini slump test (Jayasree and Gettu 2008). The natural pozzolana, in the form of volcanic ash (VA), was obtained from Jeddah, Saudi Arabia. The basic physical and chemical characteristics of the samples of VA were determined and compared with the previous studies (Al-Bahar et al. 2017; Al-Fadala et al. 2017). The solid content, pH, and specific gravity of the SP and VMA were determined according to ASTM C 494-2013. The complete characterization of the samples of cement, normal coarse aggregates (NCA), recycled coarse aggregates (RCA), and chemical admixtures was also carried out to ensure the quality control. The comparative values of the major oxides of OPC, VA and GGBS are given in Table 1 obtain basic information about the material. Similarly, the properties of aggregates are given in Table 2. The bulk density and specific gravity values of aggregates were used for developing the mix proportions of concrete.

**Table 1.** Chemical Composition of OPC, VA, and GGBS

| Property (%) | OPC | VA | GGBS |
|---|---|---|---|
| $SiO_2$ | 16.63 | 38.89 | 36.86 |
| $Al_2O_3$ | 3.63 | 13.00 | 10.95 |
| $Fe_2O_3$ | 3.28 | 12.41 | 0.94 |
| CaO | 62.27 | 9.09 | 42.39 |
| MgO | 1.22 | 6.16 | 6.54 |
| $Na_2O$ | 0.34 | 3.12 | 0.19 |
| $K_2O$ | 0.61 | 1.31 | 0.33 |

| | | | |
|---|---|---|---|
| $SO_3$ | 3.91 | 0.14 | 2.00 |
| $TiO_2$ | 0.24 | 2.44 | - |

**Table 2.** Properties of Coarse Aggregates and Sand

| Property | | Bulk density (kg/m$^3$) | Specific gravity |
|---|---|---|---|
| NCA (mm) | 20 | 1573 | 2.7 |
| | 14 | 1527 | 2.7 |
| | 10 | 1521 | 2.7 |
| RCA (mm) | 20 | 1360 | 2.3 |
| | 14 | 1343 | 2.3 |
| | 10 | 1302 | 2.3 |
| Washed sand | | 1575 | 2.5 |

## Preparation and Testing of Concrete Mixes

VC and SCC mixes with different compositions, including the replacement of ordinary Portland cement (OPC) and normal coarse aggregates (NCA) with 30% VA and 30% RCA, respectively, were prepared. The fresh state properties of VC and that of SCC, including flowing ability, passing ability, and segregation resistance were determined and compared with the acceptance criteria (EFNARC Guidelines 2005). Six concrete mixes were prepared for a designed strength of 45 MPa and the details of the mix proportions for conventional mixes of VC and SCC are given in Table 3. Two types of control mixes and four types of test mixes were prepared. The difference is that the test mixes were prepared with GGBS, recycled aggregates, and VA. Mixes were designated as follows: Mix 1: VC1- vibrated cement concrete; Mix 2: SCC1- self-compacting concrete; Mix 3: VC2- vibrated cement concrete with an OPC replacement of 50% GGBS; Mix 4: SCC2- self-compacting concrete with an OPC replacement of 50% GGBS; Mix 5: VC3- Vibrated cement concrete with an OPC replacement of 30% VA and with NCA replacement of 30% RCA; Mix 6: SCC3-self-compacting concrete with OPC replacement of 30% VA and NCA replacement with 30% RCA.

**Table 3.** Mix Proportion for 1 m$^3$ of Concrete

| Quantities of materials | Mix 1 (VC1) | Mix 2 (SCC1) |
|---|---|---|
| Cement (kg) | 475 | 475 |
| Water (L) | 167 | 167 |
| NCA 20 mm (kg) | 495 | 412 |
| NCA14 mm (kg) | 306 | - |

| | | |
|---|---|---|
| NCA 10 mm (kg) | 253 | 618 |
| Washed sand (kg) | 703 | 721 |
| Air (%) | 0.01 | 0.02 |
| Admixture 1 SP (ml) | 290 | 700 |
| Admixture 2 VMA (ml) | - | 50 |

The mechanical and durability properties of concrete mixes, including compressive strength, splitting tensile strength, flexural strength, density, water absorption, concrete resistivity, and resistance to chloride ion penetration were determined according to respective standards and specifications. A detailed description of the strength, microstructural modification and durability indices of the developed mixes were reported as first part of this study (Chakkamalayath et al., 2018; Chakkamalayath et al., 2020). However, the scope of this paper is limited to the evaluation of the cost effectiveness of different mixes, and to select an optimum mix based on the study.

## Cost Evaluation of Concrete Mixes

The cost comparison was carried out for six concrete mixes which includes control mixes of both VC and SCC, and concrete mixes containing GGBS, VA, and RCA. The total cost of concrete mixes per cubic meter was calculated based on the cost of the substances in the mix. The labor cost of VC and SCC mixes was determined based the actual labor required for each mix. In this study, a "decision matrix" method was used to evaluate different mixes, and to select the most appropriate mix in terms of cost-effectiveness and sustainability (http://asq.org/learn-about-quality/decision-making-tools/overview/decision-matrix.html). The different factors affecting the cost were evaluated, and the weightage was assigned based on its importance in the cost-benefit analysis.

# RESULTS AND DISCUSSIONS

## Cost-Benefit Analysis for VC and SCC

The benefit of using sustainable materials against conventional materials while preparing different concrete mixes was analyzed. The prevailing cost of materials and labor was collected from the ready-mix concrete (RMC) plants in Kuwait.

## Material cost

The data provided by the ready-mix companies for the cost of different materials is given in Table 4. It can be observed that the cost of GGBS is higher than OPC, as the raw material for the production of GGBS is imported from other countries. Nevertheless, based on the Gulf Co-operation council decisions on the use of regionally available material, transportation cost only is involved in the case of VA.

**Table 4.** Details of Material Cost Prevailing in Kuwait Ready-Mix Concrete Plants

| Details of Materials | Cost in Kuwaiti Dinar** | Cost in USD*** |
|---|---|---|
| Cement (Type I) (Ton) | 21.200 | 70.67 |

| | | |
|---|---|---|
| Cement (Type V) (Ton) | 22.700 | 75.67 |
| Water (Gallon) | 0.00025 | 0.00083 |
| Washed sand (Cubic meter) | 3.500 | 11.67 |
| Normal Coarse Aggregate (3/4’’, 3/8’’ and ½’’) (Cubic meter) | 9.300 | 31.00 |
| Recycled Aggregate (Cubic meter) | 6.000 | 20.00 |
| GGBS (Ton) | 31.7 | 105.67 |
| Volcanic ash* (Ton) | 24.77 | 82 |
| Superplasticizer (Liter) | 0.230 | 0.77 |
| VMA (Liter) | 0.830 | 2.77 |

Note: Electricity and Water Rates (Source: Ministry of Electricity & Water)

1 fils/Kilowatt for supported industrial companies

250 fils/1000 gallon for supported industrial companies

*only transportation cost incurred as it is regionally available

** based on the prevailing rates in Kuwait Market during 2018-19

*** based on the average exchange rate during the evaluation period.

The data analysis given above shows that the main difference between VC and SCC is the material cost and labor cost. All the other main cost items as fixed assets including land, building, machines, tools, trucks, maintenance and quality control are same.

## Labor cost

The details of casting and the number of laborers required for VC and SCC were collected from the ready-mix companies to calculate the labor cost. The following data in Table 5 was collected from a contractor and it may vary depending upon the site circumstances. The labor cost at the site for casting VC and SCC was compared based on the basic requirements of casting an approximate area of 30 square meter slab (thickness 15 cm) with an approximate concrete volume of 135 $m^3$ using one pump.

**Table 5.** Labor Cost for Casting and Placing Concrete

| | VC | | | SCC | | |
|---|---|---|---|---|---|---|
| | **Number** | **Cost (KD)** | **Cost (USD)** | **Number** | **Cost (KD)** | **Cost (USD)** |
| Labor | 10 | 15 | 50 | 6 | 15 | 50 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Vibrator | 2 | 5 | 16.67 | - | - | |
| Total Labor cost | | 160 | 533.13 | | 90 | 300 |

## Cost of concrete mixes per cubic meter

The cost of different mixes was calculated based on the cost of the materials as given in Table 4, and the results are reported in Tables 6 to 8. The total cost of concrete mixes was calculated both in Kuwaiti Dinar (KD) and in US dollars (USD). Table 6 gives the cost of materials used in Mixes 1 and 2 (both VC1 and SCC1), where OPC and normal aggregates were used. Mix 3 and 4 (both VC2 and SCC2) were prepared by replacing 50% of OPC with GGBS and the cost comparison of mixes are provided in Table 7. OPC was replaced with 30% VA, and normal coarse aggregates were replaced with 30% recycled aggregates as given in Table 8 for Mixes 5 and 6.

It can be observed from Table 6 that there is only a marginal difference between the cost of materials for control mixes of VC and SCC. Mixes 3 and 4 had a higher material cost, because of the higher cost of GGBS in Kuwait. However, the cost of both VC and SCC prepared with GGBS were comparable even after using a different mix proportion. On the other hand, the cost for Mixes 1 and 2, and Mixes 5 and 6 were almost the same, although in Mixes 5 and 6, 30% of recycled aggregates were used instead of normal aggregates, and the cost of recycled aggregates was less than the normal aggregates. VA was also used as a replacement of cement for Mix 5 and 6. However, other benefits that can be obtained while using different mixes were considered for the final selection.

**Table 6.** Cost of Concrete Mix 1 and Mix 2 per m$^3$

| **Details of** | | **VC1** | | | **SCC1** | |
|---|---|---|---|---|---|---|
| **Materials** | **Quantity** | **Cost (KD)** | **Cost (USD)** | **Quantity** | **Cost (KD)** | **Cost (USD)** |
| Cement (Type I) (kg) | 475 | 10.070 | 33.57 | 475 | 10.070 | 33.57 |
| GGBS (kg) | - | - | - | - | - | - |
| Water (kg) | 167 | 11.029 | 36.76 | 167 | 11.029 | 36.76 |
| Fly ash/VA (kg) | - | - | - | - | - | - |
| NCA 20 mm (kg) | 495 | 2.927 | 9.76 | 412 | 2.436 | 8.12 |
| NCA 14 mm (kg) | 306 | 1.864 | 6.21 | - | - | - |
| NCA 10 mm (kg) | 253 | 1.547 | 5.16 | 618 | 3.779 | 12.59 |
| Washed sand (kg) | 703 | 1.562 | 5.21 | 721 | 1.602 | 5.34 |
| SP (ml) | 290 | 0.067 | 0.22 | 700 | 0.161 | 0.54 |
| VMA (ml) | | | | 50 | 0.042 | 0.14 |
| Total weight (kg) | 2399 | | | 2393 | | |
| **Total Cost /m$^3$** | | **29.066** | **96.89** | | **29.119** | **97.06** |

**Table 7.** Cost of Concrete Mix 3 and Mix 4 per m$^3$

| Details of Materials | VC2 | | | SCC2 | | |
|---|---|---|---|---|---|---|
| | Quantity | Cost (KD) | Cost in (USD) | Quantity | Cost (KD) | Cost (USD) |
| Cement (Type I) (kg) | 237.5 | 5.035 | 16.78 | 237.5 | 5.035 | 16.78 |
| GGBS (kg) | 237.5 | 7.529 | 25.09 | 237.5 | 7.529 | 25.09 |
| Water (kg) | 167 | 11.029 | 36.76 | 167 | 11.029 | 36.76 |
| Fly ash/VA (kg) | - | - | - | - | - | - |
| NCA 20 mm (kg) | 495 | 2.927 | 9.76 | 412 | 2.436 | 8.12 |
| NCA 14 mm (kg) | 306 | 1.864 | 6.21 | - | - | - |
| NCA 10 mm (kg) | 253 | 1.547 | 5.16 | 618 | 3.779 | 12.59 |
| Washed sand (kg) | 703 | 1.562 | 5.21 | 721 | 1.602 | 5.34 |
| SP (ml) | 290 | 0.067 | 0.22 | 700 | 0.161 | 0.54 |
| VMA (ml) | | | | 50 | 0.042 | 0.14 |
| Total weight (kg) | 2399 | | | 2393 | | |
| **Total Cost /m$^3$** | | **31.560** | **105.19** | | **31.613** | **105.36** |

**Table 8.** Cost of concrete Mixes 5 and 6 per m$^3$

| Details of Materials | VC3 | | | SCC3 | | |
|---|---|---|---|---|---|---|
| | Quantity | Cost (KD) | Cost (USD) | Quantity | Cost (KD) | Cost (USD) |
| Cement (Type I) (kg) | 332.5 | 7.049 | 23.49 | 332.5 | 7.049 | 23.49 |
| GGBS (kg) | - | - | - | - | - | - |
| Water (kg) | 167 | 11.029 | 36.76 | 167 | 11.029 | 36.76 |
| Fly ash/VA (kg) | 142.5 | 3.563 | 11.88 | 142.5 | 3.563 | 11.88 |
| NCA 20 mm (kg) | 346.5 | 2.049 | 6.83 | 288.4 | 1.705 | 5.68 |

| | | | | | | |
|---|---|---|---|---|---|---|
| NCA 14 mm (kg) | 214.2 | 1.305 | 4.35 | - | - | - |
| NCA 10 mm (kg) | 177.1 | 1.083 | 3.61 | 432.6 | 2.645 | 8.82 |
| RCA 20 mm (kg) | 148.5 | 0.655 | 2.18 | 123.6 | 0.545 | 1.82 |
| RCA 14 mm (kg) | 91.8 | 0.410 | 1.37 | - | - | - |
| RCA 10 mm (kg) | 75.9 | 0.349 | 1.16 | 185.4 | 0.854 | 2.85 |
| Washed sand (kg) | 703 | 1.562 | 5.21 | 721 | 1.602 | 5.34 |
| SP (ml) | 290 | 0.067 | 0.22 | 700 | 0.161 | 0.54 |
| VMA (ml) | | | | 50 | 0.042 | 0.14 |
| Total weight (kg) | 2399 | | | 2393 | | |
| **Total Cost /m$^3$** | | **29.121** | **97.06** | | **29.195** | **97.32** |

## Decision Matrix for the Cost Comparison of the Concrete Mixes

In this study, a “decision matrix” method was used to evaluate different mixes, and to select the most appropriate mix in terms of cost-effectiveness and sustainability.

A Decision matrix: is a matrix used to evaluate different alternatives of a decision based on several criteria chosen to reach the rational decision.

In the development of the decision matrix, a table was created with all the alternatives in the first raw and all of the factors (the evaluation criteria) that affect the decision in the first column in this matrix. The weight assigned for each evaluation criteria is based on its importance to the prevailing situation in the country. The final score was calculated to find the best alternative.

The evaluation criteria appropriate to the situation was decided among the research group and this was further refined and finalized in consultation with the experts in the field. According to that, the criteria that must be included were finalized. The list of criteria was reduced in such a way that the most important ones are included in the study. Relative weight was assigned to each criterion. Each alternative against the criteria was evaluated in as follows:

Step 1: In order to reach a decision and distinguish among the alternatives a rating scale must be set. There are many scales options. One of them is chosen, as an example:

- 1, 2, 3 (1 = low, 2 = medium, 3 = high)
- 1, 2, 3, 4, 5, 6 (1 = little to 6 = great)
- 1, 4, 9 (1 = low, 4 = moderate, 9 = high)

The rating scales were made reliable, and the criteria and scales were set in such a way that the high end of the scale (9 or 6 or 3) was representing that particular alternative, which has the most impact on customers, greatest importance, least difficulty, and the greatest likelihood of success.

Step 2: The different alternatives were given a certain value from the scale that was chosen depending on the suitability of the criterion. It was numbered in such a manner that 1 being the alternative that is least desirable according to that criterion.

Step 3: Each option's rating was multiplied by the weight and the total points for each alternative were added. The relative scores were compared to make the final selection.

The various factors (evaluation criteria), its weightage and the corresponding cost effectiveness of six concrete mixes are given in Table 9 to evaluate the most appropriate mix. As mentioned earlier, the following steps were done: In the first step, weighting was done for the criterion. A value from 1 to 5 was assigned according to the importance of this criterion. Ten criteria were used in this study, and they were derived from the literature review and expert's opinion. Accordingly, based on the scarcity of material in Kuwait, except sand other construction material were imported, so material cost was weighted 4 and the labor cost was an important criterion as Kuwait is heavily dependent on the expatriate labor force, so the labor cost was weighted 3.

Rating scale**:** The studied mixes were giving a scale value according to the appropriateness of them with each criterion. It was numbered in such a way that 1 being the alternative that is least desirable according to that criterion and 6 was the most desirable. Depending on the total score, the mix that was better to be used or having maximum score in cost-benefit analysis was chosen.

**Table 9.** Cost Comparison of Concrete Mixes

| | **Weight** | **VC 1** | **SCC 1** | **VC 2** | **SCC 2** | **VC 3** | **SCC 3** |
|---|---|---|---|---|---|---|---|
| Material Cost | 4 | 6 | 5 | 2 | 1 | 4 | 3 |
| Labor Cost | 3 | 3 | 6 | 3 | 6 | 3 | 6 |
| Equipment wear | 2 | 2 | 4 | 2 | 4 | 2 | 4 |
| Safety/Health | 4 | 2 | 3 | 2 | 3 | 2 | 3 |
| Noise | 3 | 1 | 6 | 1 | 6 | 1 | 6 |
| Environment friendly | 5 | 2 | 2 | 4 | 4 | 6 | 6 |
| Energy conservation | 5 | 1 | 2 | 3 | 4 | 5 | 6 |
| Scarcity of resources | 4 | 1 | 1 | 3 | 3 | 5 | 5 |
| Easiness of placement | 3 | 2 | 4 | 2 | 4 | 2 | 4 |
| Durability | 5 | 1 | 2 | 5 | 6 | 3 | 4 |
| **Total Score** | | **78** | **122** | **110** | **154** | **136** | **180** |

SCC 2 and SCC 3 had a higher total score which demonstrates the preference of SCC over VC. The highest score was obtained for SCC 3, which implies the benefit of using regionally and locally available VA and RCA instead of imported GGBS and NCA, respectively. It was further confirmed that the initial cost of VC and SCC was the same for different combinations. In addition, the benefit obtained while preparing SCC with locally and regionally available materials was more than that of VC.

As reported in the first stage of the study, these concrete mixes had also satisfied the strength and durability requirements (Chakkamalayath et al. 2020). Nevertheless, the mechanical properties of the optimum mix obtained from the cost-benefit analysis, containing VA and RCA (SCC 3), was compared with the control mixes of VC and SCC. It was reported that the control mixes, VC 1 and SCC 1 had achieved the designed strength of 45 MPa within

28 days. Even though the mix containing 30% VA and 30% RCA (SCC 3) could not achieve the designed strength within 28 days, it had attained the required strength after 90 days of curing.

## CONCLUSIONS AND RECOMMENDATIONS

The cost analysis of VC and SCC mixes containing conventional materials, and alternate materials confirmed that the initial cost of both mixes was same. Moreover, other cost items were the same except the labor cost, which was less in the case of SCC. SCC has also added advantage in terms of social, environmental and maintenance aspects. Hence, the scope of using SCC could be extended to mass housing and infrastructure solutions for ensuring quality in construction. The comparison of mixes also showed the advantages of incorporating locally available recycled aggregates and regionally available VA to produce cost effective and sustainable concrete mixes. Therefore, the optimum mix based on the Decision matrix tools was SCC3 incorporating VA and RCA based on the selected criteria. It could establish through the study that the selected regionally available sustainable materials can be considered as possible alternatives to meet the raw material scarcity in Kuwait, with an eventual usage in the construction industry. This study further recommends the importance of conducting Cost-Benefit analysis of the concrete mixes containing alternate materials before selecting any mix for construction projects.

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