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Efficiency evaluation of recycled concrete based Data Envelopment Analysis (DEA) approach

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Abstract

The construction industry is one of the primary energy consumers, since the production of building materials requires an enormous amount of energy. Therefore, the industry needs to consider the sustainability of utilizing natural resources, focusing on reducing the embodied energy that is used in the production of concrete. This paper presents the results of the evaluation efficiency of recycled concrete based on the Data Envelopment Analysis (DEA) approach. First, it presents the experimental results of the mechanical properties of concrete samples that consisted of different percentages of recycled concrete aggregate. Second, the efficiency of each concrete mix design alternative is considered in terms of embodied energy and material cost. Further, the overall efficiency of each proposed concrete mix design alternative is considered in terms of their related mechanical properties, cost and embodied energy that is consumed during the production stage.

Keywords: Recycled concrete, Evaluation efficiency, Data Envelopment Analysis (DEA)

INTRODUCTION

Saudi Arabia is a member of the G20 Group, and it has the biggest economy in the Middle East. In 2016, it approved its long-term economic transformation plan, namely Vision 2030, which outlines a program for a more balanced growth and socio-economic development that would be aligned with sustainability principles [1]. In this context, Saudi government is undertaking significant steps to reconfigure its business model through adopting measures to transition from oil-based to sustainable economies and continue infrastructure investment [2] .

The main objective of sustainable development principles is to reduce the use of natural resources in the production and consumption industry [3]. One of the top consumers of natural resources is the construction industry. Consequently, construction and demolition (C&D) waste creates a major percentage of total solid waste production globally, most of which is used in land fill [4]. For example, in 2006, in the European Union, the construction industry was responsible for generating around 970 million tons of waste per year [5]. This represents around 25% to 30% of the total amount of waste produced. In the USA, around 136 million tons of construction waste was generated in 1996 [6]. This amount of construction waste has been estimated to constitute approximately 29% of total solid waste in the USA [7]. In Saudi Arabia, the Ministry of Municipal and Rural Affairs [8] estimated that the construction solid waste, including wood, steel, concrete, blocks, and other items, amounts to 45% of the total municipal waste in Saudi Arabia. Therefore, it is essential for the construction industry to utilize solid waste and recycled materials to decrease the pressure on natural energy and resources [9].

Construction related energy consumption is a critical issue worldwide. As stated by Energy Information Administration (EIA), buildings consumed about 29% of global energy in 2007 [10]. Concrete production is one of the largest energy consumers in the construction industry, as it involves cement and aggregate production. In recent years, annual world cement production has grown from 1.0 billion tons to approximately 1.7 billion tons, which is enough to produce 1 m^3 of concrete per person [11]. This significant increase in cement production has been associated with a significant increase in the cement industry's absolute energy use and CO^2 emissions. A summary of embedded energy for concrete production is presented in Table 1 [12] [13].

Table 1: Energy for concrete production [12] [13].

Constituent	Energy (MJ/kg concrete)
Coarse aggregate	0.028
Fine aggregate	0.028
RCA production	0.034
Portland cement	0.735
Water	0.000
Concrete mixing	0.0069
Materials transport	19.0

Many studies have been conducted on energy consumption in concrete production. For example, McIntyre et al. [13] propose life-cycle inventory models of the production of recycled concrete aggregate from construction waste. The researchers emphasized the importance of transportation distances in terms of increased energy saving during the production phase of concrete. On the other hand, they argued that increasing the recycled concrete aggregate (RCA) amount in concrete production will require additional cement to maintain a specified concrete compressive strength, which will lead to increasing embodied energy, as cement production is the main contributor to energy consumption in concrete production. Marinković et al. [14] studied and compared the environmental effects of the production of two types of ready-mixed concrete, natural concrete aggregate (NCA) and recycled concrete aggregate (RCA). The results of their study showed that the effects of aggregate and cement production phases are slightly larger for RAC than for NAC but that the total environmental effects depend on the natural and recycled aggregate transport distances and on transport types. Heravi et al. [15] studied energy consumption during materials and building components production and the construction of concrete and steel frames of 14 residential buildings in an Iranian context. They stated that the main contributor to energy consumption in concrete production is the production stage of materials, which involves cement and aggregate production respectively. Wijayasundara et al. [16] evaluated the embodied energy of RCA received at a construction site and compared it to that of NCA using the input-output-based hybrid approach based on a data collected from an Australian construction industry. The authors developed a model to assess the embodied energy of RCA and analyzed the incremental energy of RCA, as opposed to NCA, to identify the factors that contributed to the difference in energy consumption. They found that the binder composition, the cement in their case, is the greatest contributor to energy consumption.

Therefore, the main objective of this paper is to examine the effectiveness of the data envelopment analysis in efficiency evaluation of recycled concrete and to investigate the effect of improving mechanical properties of alternative concrete mixes on their embodied energy and production cost. The rest of this paper is organized as follows. Section 2 describes the proposed methodology, including the data envelopment analysis (DEA) used to design the proposed assessment model. Section 3 summarizes the results of applying the proposed assessment model. In Section 4, we discuss and interpret the obtained results . Finally, we summarize the findings and offer conclusions.

METHODOLOGY

The research methodology of this paper is divided into two parts, as can be seen in Figure 1. First, the experimental work aimed to determine the mechanical properties of alternative concrete mixes proposed in this paper. Second, the data envelopment analysis (DEA) was utilized to determine the efficiency score for each concrete mix design proposed in this study.

A. Data envelopment analysis

The data envelopment analysis (DEA) is an application of linear programming based on Farrell's frontier approach [17] . In this study, DEA proposed as performance assessment approach due to its strengths compared to other traditional approaches. The main advantages of DEA method are [18] that it (1) can handle multiple inputs and multiple outputs simultaneously, (2) does not require relating inputs to outputs, (3) facilitates direct comparisons with competitors, and (4) allows inputs and outputs to have very different units.

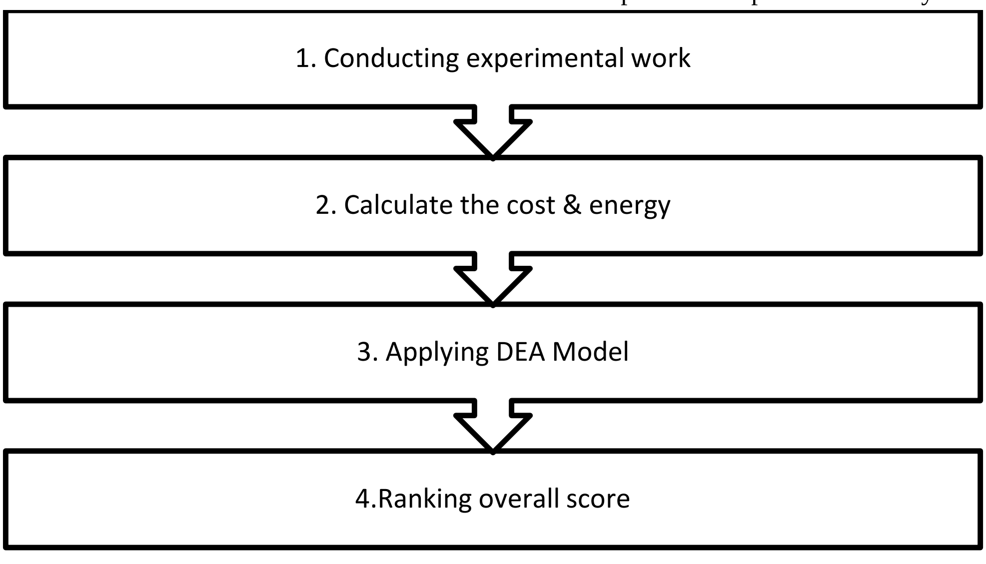

Figure 1. The research methodology

DEA is a known technique that is applied to assess and improve the operational performance of various processes within many industries. Its recent applications cover many fields, such as banking [19], supplier selection [20], and energy utilization [21]. In the construction industry, DEA has been used to examine matters such as the eco-efficiency of construction materials [22], bridges for maintenance planning [23], and efficiency of the maintenance of paved lanes [24].

Based on the above, we used the DEA model in this study. First, we determined the efficiency score for each concrete mix design proposed in this study while considering the cost and embodied energy related to each. Second, we explored the potential improvements in selected mechanical properties of concrete mix design alternatives which are compressive and tensile strength, which are considered as DEA outputs. Its effect of improving outputs factors on input factors of cost and embodied energy was also considered. In this study, the proposed DEA model was expressed using two inputs and two outputs. The two inputs were cost and embodied energy. The two outputs were compressive strength and tensile strength. The data regarding the input factors has been collected as follows; the cost of concrete production has been collocated from the construction industry market, and the embodied energy has been extracted from related published studies. Concerning the output data, the experimental results of the mechanical properties of proposed concrete mix design alternatives in this study have been used in DEA analysis.

Various DEA mathematical models are available in literature. In this paper, we employed the input oriented CCR model (CCR refers to Charnes, Cooper, and Rhodes; [25]) This model can be mathematically expressed as:

$$\min \theta - \varepsilon\left\{\sum_{k=1}^{m} s_k^- + \sum_{i=1}^{r} s_i^+\right\}$$

subject to

$$\theta x_{ko} - \sum_{j=1}^{n} x_{kj}\lambda_j - s_k^- = 0, \quad k=1,\dots,m, \tag{1}$$

$$\sum_{j=1}^{n} y_{ij}\lambda_j - s_i^+ = y_{io}, \quad i=1,\dots,r,$$

$$\lambda_j, s_k^-, s_i^+ \geq 0,$$

Where λ_j is the weight given to alternative; s_k^- and s_i^+ represent the slack for input *i* and the surplus for output k, respectively. Note that ε is an arbitrarily small positive number employed to ensure that none of the considered inputs and outputs are negative. In this situation, technical efficiency for each alternative is achieved if, and only if, both of the following conditions are fulfilled: 1- All slacks = 0; 2- Efficiency score =1.

B. Experimental program

The experimental work aimed to determine the mechanical properties of the alternative concrete mix that has been cured for 7, 14, and 28 days. It has used locally available materials, namely sand, gravel, and cement. Moreover, recycled concrete aggregate from the demolition of concrete structures was processed with a jackhammer to reduce its size and then used in related concrete mix alternatives. Embedded energy and production cost related to alternative concrete mix have been calculated to rank each proposed concrete mix alternative. A concrete mix with natural aggregate (NA) and three concrete mixtures of the same w/c ratio as recycled concrete aggregate (RA 25%, RA 50%, and RA 100%) were produced and tested in this study. A concrete cylinder with compressive strength of 35 MPa was targeted in this study. This can be achieved using local materials at a w/c ratio of around 0.43. Recycled concrete aggregate was added at different proportions, specifically 25% (RA 25%), 50% (RA 50%), and 100% (RA-100%). The concrete mix proportions for all mixes are presented in Table 2. All mixes were prepared in the lab using a laboratory mechanical drum mixer.

Table 2: Mix proportions (kg/m^3) of each mix design alternative

Mix	Water-cement ratio	Cement	Water	Sand	NA	RA	Admixture
NA	0.43	410	182	789	1047	0	7.9
RA 25%	0.43	410	182	789	786	261	7.9
RA 50%	0.43	410	182	789	523	523	7.9
RA 100%	0.43	410	182	789	0	1047	7.9

Specimen preparation and testing

Three specimens representing the same component were used for each test during this study, and the average values are reported. Cylindrical concrete specimens, 75 mm in diameter and 10 mm high, were prepared to evaluate the compressive strength. The compressive strength was determined according to ASTM C 39 after 7, 14, and 28 days of water curing. The compressive load was subjected to specimens using a servo-hydraulic compression machine. Other specimens were prepared to evaluate the split tensile strength. They were tested for split tensile strength according to ASTM C 496 after 7, 14, and 28 days of water curing.

RESULTS

This section outlines the results of this study. It provides the mechanical properties of proposed concrete samples that consisted of different percentages of recycled concrete aggregate. It further describes the application of DEA methodology to determine the efficiency of each concrete mix design alternative while considering embodied energy and material cost.

A. Mechanical properties results

Compressive strength

Three concrete specimens were prepared for each concrete design mix alternative that included natural aggregate (NA) and recycled aggregate (RA) with different percentage 25%, 50%, and 100%. All specimens were designed with a compressive strength of 35 MPa. The compressive strength of each specimen was tested according to ASTM C109/C109M – 13 at 7, 14, and 28 days. The results indicated that at 28 days, the concrete mix designed with natural aggregate samples exceeded the design strength of 35 MPa and had the highest strength. The specimens made from 100% recycled waste aggregate were had a weaker strength at 34.11 MPa, whereas the specimens made from 25% percent of recycled aggregate showed higher strength of 37.7% after 28 days indicates. However, the design concrete mix with 50% recycled aggregate had a slightly increased over design strength.

Table 3: Average compressive strength (MPa) for each mix design alternative

Curing time (Days)	NA	RA 25%	RA 50%	RA 100%
7	32.77	31.63	30.53	29.48
14	34.03	33.1	31.85	31.1
28	39.98	37.7	36.04	34.11

Tensile strength

This study also investigated another mechanical property using the split tensile strength test to compare concrete made with natural aggregate from local material and recycled aggregate from construction waste. Three specimens for each mix deign alternative were tested at 7, 14, and 28 days (Table 4). The split tensile strength of the concrete specimens made with the natural aggregate was generally higher compared to the strength of the specimens made with recycled waste aggregate, especially at 28 days. It was found that the concrete sample made from 25% recycled aggregate and the rest from natural aggregate provided better results compared to samples using 50% and 100 % of recycled aggregate in their concrete mixes.

Table 4: Average Split tensile strength (MPa) of each mix design alternative

Curing time (Days)	NA	RA 25%	RA 50%	RA 100%
7	2.29	2.23	2.13	2.03
14	2.75	2.58	2.42	2.16
28	3.12	2.85	2.69	2.45

B. DEA Results

As mentioned above, the main objective of using the DEA approach in this study was to calculate the overall efficiency for each proposed concrete mix design alternative, taking in consideration their related cost and the embodied energy that would be consumed during production stage. Thus, the data on the cost and embodied energy for each of the alternatives has been calculated and presented in Table 5. The data was then analyzed and the results were produced using specialized software for DEA (Frontier Analyst). The results showed that three out of the four concrete mix alternatives were inefficient, specifically, RA 25% (95.4%), RA 50% (92.9%), and RA 100% (91.6%), as shown in Figure 2. Accordingly, potential improvements have been calculated for the three inefficient alternatives. The results are summarized in Table 6. Figures 3, 4, and 5 present the potential improvements for RA 100%, RA 50%, and RA 25%, respectively.

Table 5: Inputs and outputs for the four concrete mix alternatives

	Inputs		Outputs	
Concrete Mix alternatives	Cost	Embodied Energy	Compressive strength after 28 days	Tensile Strength After 28 days
NA	200	3218.30	39.98	3.12
RA 25 %	207	3102.1	37.7	2.85
RA 50 %	214	2983.9	36.04	2.69
RA 100 %	228	2749.53	34.11	2.45

Table 6: Overall results

		Potential Improvements for Inputs		Outputs	
Concrete mix alternatives	Efficiency score	Cost	Embedded Energy	Compressive strength after 28 days	Tensile strength after 28 days
NA	100	0	0	0	0
RA 25 %	95.4	-5%	1%	4%	7%
RA 50 %	92.9	-10%	3%	6%	11%
RA 100 %	91.6	-20%	6%	6%	16%

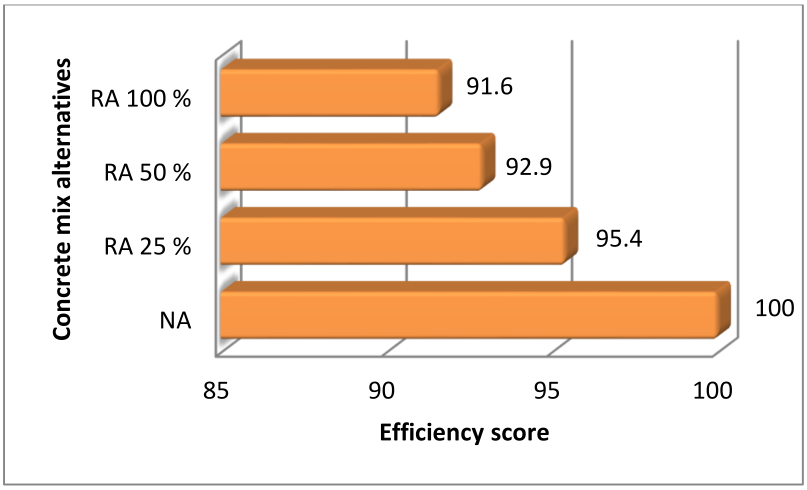

Figure 2. Concrete mix alternatives' Efficiency score

Figure 3: Potential improvements for RA 100%

Figure 4: Potential improvements for RA 50%

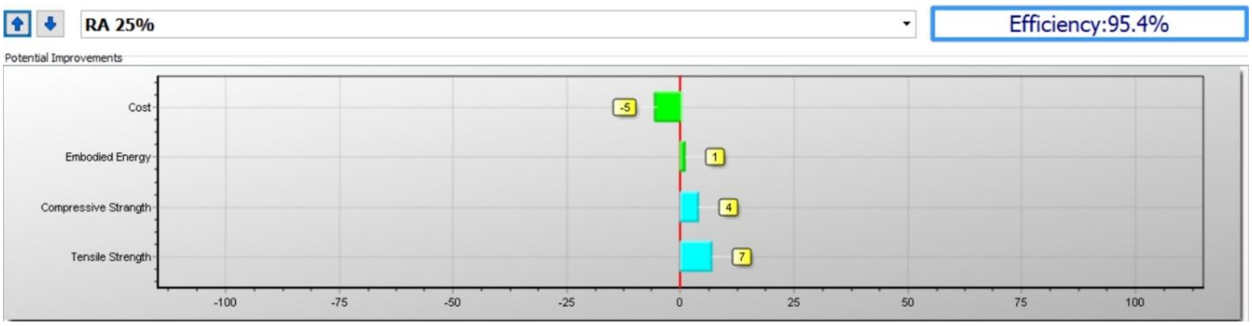

Figure 5: Potential improvements for RA 25%

DISCUSSION

The results support the strength of the application of DEA approach in evaluating the efficiency performance of recycled concrete compared to other approaches that used in literature. The proposed approach has the ability to compute the efficiency performance based on linking the inputs factors to outputs factors. Additionally, the DEA processes have shown their capability to utilize variety of factors with different units without the need to convert all factors' units to one unit. This makes the DEA a more straight forward approach, as it eliminates the number of steps needed to calculate the efficiency performance.

Regarding the DEA results explained above, the efficiency results of concrete mix alternatives have shown that the concrete mix sample (NA) made 100 percent from natural aggregate has the top efficiency score, unlike other alternatives made by adding different percentage of recycled concrete aggregate. The concrete mix sample (RA 100%) made 100 percent from recycled concrete aggregate had the lowest efficiency score. Nevertheless, less embodied energy was required to produce recycled concrete samples (RA 100%) compared to concrete sample made from natural aggregate (NA). This is because other factors, which are the cost of materials and mechanical properties (compressive strength and tensile strength) were better for concrete natural aggregate compared to that made from recycled aggregate.

Concerning the second objective of this paper. which was to investigate the effect of improving mechanical properties of alternative concrete mixes on their embodied energy and production cost, Table 6 illustrates that DEA results show that enhancing the mechanical properties of concrete mix made from recycled aggregates and reducing their production cost at different percentages can potentially to improve the efficiency of concrete mix design alternatives.

For example, to improve the efficiency of concrete mix design alternative (RA 25%), production cost can be reduced by 5%. Conversely, embedded energy will be increased by 1% over its current value, as shown in Figure 5. This means that the production cost of RA 25% will be 196.65 (SAR) instead of 207 (SAR) while the embedded energy will be 3412.31 MJ/Kg instead of 3102.1 MJ/Kg. This will increase the compressive strength by 4% and tensile strength by 7%. Similarly, regarding the RA 50% concrete mix design alternative, the DEA model results demonstrated that it is possible to improve the values of mechanical properties by increasing compressive strength by 6% and tensile strength by 11%, as shown in Figure 4. Production cost could be reduced by 10%. Accordingly, production cost of RA 50% could be 192.6 (SAR) instead of 214 (SAR). Further, embedded energy will increase by 3%, as the embedded energy will be 3073.4 MJ/Kg. Finally, regarding the RA 100% concrete mix alternative, the model results showed that the compressive strength and tensile strength would be enhanced by 6% and 16%, respectively, as shown in Figure 3. This will be reflected through input factors, as the production cost is likely to decline by 20% while embedded energy is likely to increase by 6%. As a result, the production cost of RA 100% would be 182.4 (SAR) instead of 228 (SAR), and embedded energy would be 2914.5 MJ/Kg instead of 2749.53 MJ/Kg.

CONCLUSION

Many research papers have been published on recycled construction materials in concrete production, demonstrating the feasibility of using crushed concrete as a coarse aggregate. This paper presents research results of the evaluation of efficiency performance of recycled concrete using the DEA approach. The data that has first been used in the model was extracted from real experiments that were conducted to establish the mechanical properties of concrete made by recycled concrete aggregates. This DEA application is a novel approach that has not been used before. The DEA analysis has proven its effectiveness in computing the efficiency performance of recycled concrete. The results presented here revealed the value of this approach while accounting for the amount of inputs factors, which are embedded energy and production cost, relative to outputs produced, which are mechanical properties. This type of top level study is perhaps beneficial in early investigation of a new proposed concrete mix design for comparing different alternatives and examination of the relationship between the inputs and output factors. Further research could be include more input and output factors, such as Greenhouse Gas (GHG) Emissions of the concrete, among others. Additionally, the DEA could be used at the low-level analysis to determine its competency to optimize concrete materials composition itself in order to improve the concrete strength.

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