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INVESTIGATION OF MECHANICAL PROPERTIES OF RECYCLED CONCRETE WITH ITS RELATED EMBODIED ENERGY AND PRODUCTION COST: SAUDI ARABIAN BASED STUDY

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ABSTRACT: This paper presents research results for evaluating effects of utilizing recycled concrete aggregates on the mechanical properties of concrete and its related production cost and embedded energy. The research methodology of this paper includes an experimental work has been designed to determine the mechanical properties of the alternative concrete mix at ages 7, 14, and 28 days, then production cost and embedded energy for each concrete mix were calculated. The results show that the strength of proposed mix design concrete has been negatively affected by recycled concrete aggregate, and the cost of producing recycled concrete is more expensive than ordinary concrete. However, the embedded energy that is utilized in producing recycled concrete is less than ordinary concrete. The originality of this research is based on experiments that are conducted to determine the mechanical properties of concrete made by recycled concrete aggregates and its related cost of production and embedded energy.

Keywords: Recycled concrete aggregates, Embedded energy, Cost of concrete materials, Saudi Arabia.

1. INTRODUCTION

Saudi Arabia has experienced an exceptional construction boom over the past decade, as the country's infrastructure has experienced rapid development (including railway, airports, public and private buildings, highways, etc.), which have made the Saudi Arabian construction industry one of the biggest in the world. Also, The Saudi Arabian construction industry is expected to grow over the next few years, with projects estimated at over US $735 billion as reported by [1].

This has accordingly led to escalations in stresses on raw construction materials, such as aggregate and sand that are used during construction projects. Furthermore, the construction industry in Saudi Arabia uses 14% of the total energy consumption in the country [2]. Thus, there is huge degradation of national natural resources, and there is a great need to discover another source for construction materials in order to reduce raw material utilization and to relieve the pressure on natural resources. In the Saudi Arabian context, there is a real need to promote the use of recycled materials in the construction industry, in an attempt to reduce the enormous consumption of raw materials, as well as to take advantage of the waste materials from the demolition of buildings resulting from the current boom in infrastructure development and restoration of urban planning in most Saudi cities.

The recycling of concrete waste into recycled concrete aggregate (RCA) by crushing concrete lumps into smaller particles has been identified as a potential source of alternative aggregate for production of environmentally friendly concrete [3]. However, the use of RCA for concrete production is not simply applied, because the properties of RCA are different from natural aggregates. Thus, more research must be carried out in relation to the use of recycled concrete aggregate (RCA) in concrete production from different perspectives such as the strength of concrete, embedded energy, and the total cost of production.

The main objective of this paper is, therefore, to investigate the influence of different percentages of RCA on the mechanical properties of concrete. The study also assesses the influence of the percentage of RCA quantity on embedded energy that is utilized in production concrete and its production cost based on the Saudi construction market. The next section provides a review of related literature. In the following sections, provides a description of the experimental program conducted in this study, and the results obtained from the experimental work are presented.

2. LITERATURE

A significant amount of research work has already been carried out to explore recycled construction materials in concrete production and demonstrate the feasibility of the use of crushed concrete as coarse aggregates.

In a study by Sagoe-Crentsil and Brown [4], it was found that the processing of recycled concrete aggregates commercially produces smoother spherical particles than those produced in the laboratory, which improves concrete workability. Tests on the compressive and tensile strengths of hardened concrete showed no significant difference between recycled concrete and concrete made with natural aggregates. Investigation of the durability indicated that the recycled aggregates caused a higher drying shrinkage values and reduced the abrasion resistance by about 12%. The water absorption and carbonation rates showed little difference between the recycled concrete and conventional one.

There are a number of factors that may affect the quality of concrete made with RCA in terms of compressive strength, including the percentage of coarse aggregate replaced with RCA, the amount of adhered mortar on the RCA, and the water/cement (w/c) ratio (McNeil and Kang, 2013) [5]. Most research recommended that, without changes to the mix involving adjustments to the w/c ratio, up to 25 or 30 % of coarse aggregate can be replaced with RCA before the ceiling strength is compromised. In a study by Limbachiya et al. [6], concrete specimens made with up to 30 % RCA had equal compressive strengths for w/c ratios greater than 0.25, which shows trends for compressive strengths for three RCA fractions as they vary with w/c ratio. The data for 30 % RCA follows that of 0 % RCA for almost every w/c ratio tested, while the 100 % RCA data lie at compressive strength values below that of 0 or 30 % RCA by about 5 N/mm2. At the lowest w/c ratios, the compressive strengths for mixes with RCA become more dissimilar to conventional concrete [7] found similar behavior with tests using 25 % RCA that also performed conventional concrete with the same w/c ratio. This study tested concrete made with 0, 25, 50, and 100 % RCA concrete mixes and concluded that up to 25 % could be replaced without significant change in compressive strength or a different w/c ratio; however, to obtain the same strength with 50–100 % RCA, w/c ratio needed to be 4–10 % lower, and without this alteration, the compressive strength for 100 % RCA mixes was reduced by 20–25 % [7].

Tabsh and Abdelfatah [8] investigated the strength of concrete made with coarse RCA. The variables that are considered in the study include the recycled concrete and target concrete strength. The toughness and soundness test results of the RA coarse aggregate concrete showed higher loss than in concrete with natural aggregate but remained within the acceptable limits. The compressive and splitting tensile strengths of concrete made with recycled coarse aggregate depend on the mix proportions. It was found that the strength of recycled concrete can be 10–25% lower than that of conventional concrete. Puthussery et al [9] studied the recycling potential of waste concrete as aggregated in construction activities. In this study, six concrete mix designs were prepared, three each with recycled coarse aggregate (RCA) and recycled fine aggregate (RFA) in different replacement percentage which are 25, 50, and 100% for both aggregates. They found that there is no significant difference noted in the compressive strength of various concrete mixes prepared by natural and recycled aggregates. However, they observed a decrease in the tensile strength in concrete mix as the percentage amount of recycled aggregate content increased. It is recommended in their study that replacement of 25% natural fine aggregates by recycled fine aggregates will be the best proposition.

3. EXPERIMENTAL PROGRAM

The experimental work has been designed to determine the mechanical properties of the alternative concrete mix that is proposed in this paper at ages 7, 14, and 28 days. It has used locally available materials, namely sand, gravel, and cement. Also, the recycled concrete aggregate is used for the demolition of concrete structures. This was processed with a jackhammer to reduce its size and then used in related concrete mix alternatives.

A concrete mix with natural aggregate (NA) and three concrete mixtures of the same w/c ratio with recycled concrete aggregate (RA 25%, RA 50%, and RA 100%) were designed and tested in this study. A concrete cylinder with a compressive strength of 35 MPa was targeted in this study. This can be achieved with local materials at a w/c ratio of around 0.43. Recycled concrete aggregate was added at different proportions ranging from 25% (RA 25%), 50% (RA 50%), to 100% (RA-100%). The concrete mix proportions are presented in Table 1. The mixes were prepared in the lab using a laboratory mechanical drum mixer.

Table 1 Mix proportions (kg/m^3) of each mix design alternative

Mix	W-C	C	W	S	NA	RA	Ad
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

W/C: Water cement ratio; C: Cement; W: Water; S: Sand; NA: Natural aggregate; Recycled Aggregate; AD: Admixture

3.1 Physical Properties of Natural and Recycled Aggregate

Tests related to aggregate, such as sieve analysis, resistance to degradation of coarse aggregate by impact in the Los Angeles machine, relative density (specific gravity), absorption, bulk density (unit weight) and voids in aggregate, were conducted in order to investigate the engineering properties. Based on the specifications of ASTM C29/C29M – 09, the results obtained show that the bulk densities of the recycled aggregate were slightly higher than the natural aggregate, whereas the number of voids was less as can be seen in Table 2. Regarding the specific gravity and absorption test, the results show that the specific gravity increases as the absorption decreases. Concerning the specific gravity of the recycled aggregate, it was lower than that of the natural aggregate whereas the absorption of recycled aggregate is higher than the natural aggregate; this is because of the cement attached to the recycled concrete aggregate particles.

Table 2 Physical properties of natural & recycled aggregate

Physical properties	Recycled Aggregate	Natural Aggregate
Volume of cylinder	0.0053	0.0053
Unit weight (kg/m^3) - ASTM C29 / C29M -	1485.0	1478.1
Voids (%) - ASTM C29 / C29M - 09	29.5	34.5
Bulk specific gravity	2.11	2.43
Apparent specific	2.32	2.531
Water absorption (%)	3.92	1.73
Loss of abrasion and impact (%)	30%	24%

3.2 Specimen Preparation and Testing

Three specimens representing the same component were used for each test during this study and the average values were reported. Cylindrical concrete specimens, 75 mm in diameter and 10 mm high, were prepared to evaluate 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. Prism concrete specimens of size 100 x 100 x 500mm were prepared to find out flexural strength according to ASTM C 293.

4. RESULTS

The results are presented in this section: first, to discover the mechanical properties of proposed concrete samples that consisted of different percentages of recycled concrete aggregate. Second the determine the embodied energy and material cost of each concrete mix design alternatives.

4.1 Mechanical Properties Results

4.1.1 Compressive strength

Three concrete specimens were prepared with the aggregate for each concrete design mix alternatives that included natural aggregate (NA), and recycled aggregate (RA) with different percentages: 25%, 50%, and 100% (Figure 1). 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 indicate 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 below design strength, with a value of 34.11 MPa, whereas the specimens made from 25% percent of recycled aggregate were above design strength, as its value was 37.7% after 28 days. However, the design concrete mix with 50% recycled aggregate was slightly above the design strength.

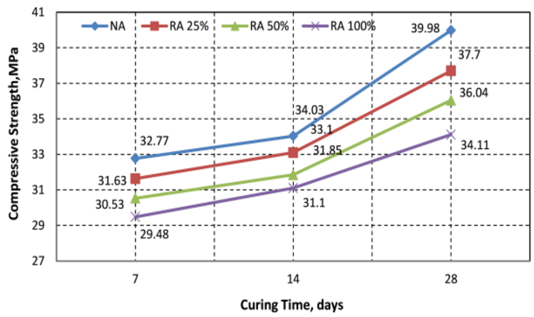

Fig. 1 Average Compressive strength (MPa) of each Mix Design Alternative

4.1.2 Tensile strength

Another mechanical property was investigated in this study, namely through the split tensile strength test. It was used to compare concrete made with natural aggregate from local material, and recycled aggregate from construction waste. Three specimens for each mix design alternatives were tested at 7, 14, and 28 days (Figure 2). The split tensile strength of the concrete specimens made with the natural aggregate was generally higher than the strength of the specimens made with recycled waste aggregate, especially at 28 days. Moreover, the tests for the split tensile strength of specimens made with different percentages of recycled aggregate found that the concrete sample made from 25% of recycled aggregate and the rest from natural aggregate gave better results compared with that of samples which used 50% and 100% of recycled aggregate in preparing their concrete mixes.

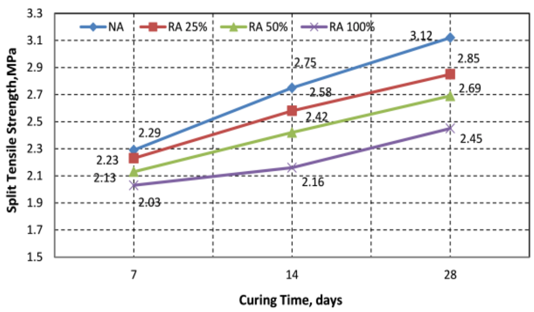

Fig. 2 Average Split tensile strength (MPa) of each Mix Design Alternative

4.1.3 Flexural strength

The flexural strength experiment was conducted in accordance with ASTM C78 for each cure age and the average strength was computed to compare the strength of proposed concrete mix design alternatives in this study. Three specimens for each alternative were tested at 7, 14, and 28 days (figure 3). The flexural strength of the specimens of NA concrete mix alternatives which were made from natural aggregate was higher overall than the specimens for all other concrete mix alternatives that made by the different percentage of recycled aggregate. The concrete mix alternative with 25% of recycled aggregate specimens had higher flexural strength values than 50% and 100% of recycled aggregate specimens for concrete mix alternatives. Finally, the concrete mix alternative with 100% of recycled aggregate specimens was found to have the lowest flexural strength result compared with other alternatives.

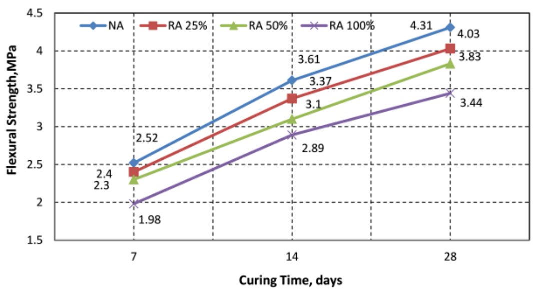

Fig. 3 Average Flexural strength (Mpa) of each Mix Design Alternative

4.1.4 Schmidt hammer

The Schmidt hammer test was used to investigate the strength of concrete specimens made with natural aggregate and recycled aggregate from construction waste. Three specimens were made for each proposed concrete mix design alternatives and these were then tested (Figure 4). The NA alternative with concrete specimens made of natural aggregate had the lowest values for all curing time, while RC 100% mix design, which was made from 100% recycled aggregate, had the highest value compared with other compositions. On the other hand, changing the percentage of recycled aggregate in other mix design indicated that the recycled coarse aggregate has a negative effect on results, as when it increased, the Schmidt hammer test value increased, as it can be seen in Figure 4 for RA 25 %, 50%, and 100% respectively.

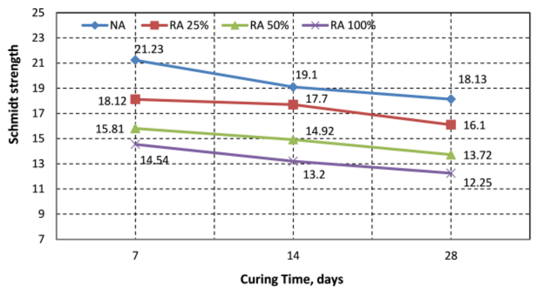

Fig. 4 Average Schmidt hammer of each Mix Design Alternative

4.2 Embodied Energy for Concrete Materials Production

The embodied energy consumed in the production of the concrete samples consists of materials production energy, manufacturing energy, and transport energy. The results of calculation for each concrete mix alternatives are presented in Table 3. The concrete mix alternatives that utilized recycled concrete aggregate have lower embedded energy values than those that only use natural aggregate. This result can be justified mainly by the difference in energy transport of both recycled and natural aggregate since the recycled aggregate normally has to be collected from the close site than the natural aggregate.

As can be seen in the results, the main contributors to energy consumption in concrete production are materials transport, since its percentage contribution to total energy was around 87 %. This is then followed by the energy of Portland cement production, comprising 11% of the total energy consumed. Other factors such as concrete mixing energy and other materials including coarse aggregate, fine aggregate, and recycled concrete aggregate only represent 2% of the total energy. This demonstrates the need to use low energy transport alternatives where possible in order to reduce the energy of transport. Furthermore, this proves the importance of utilizing new alternative binders, rather than the Portland cement that is not consuming a lot of energy on their production stage.

Table 3. Embodied energy for concrete materials production for Mix Design Alternative.

Energy Data	NA	RA 25%	RA 50%	RA 100%
Coarse aggregate	29.316	21.98	14.66	0
Fine aggregate	22.09	22.09	22.09	22.09
Portland cement production	301.35	301.35	301.35	301.35
Concrete mixing	15.49	15.49	15.49	15.49
RCA production	0	8.89	17.8	35.6
Materials transport	2850	2732.25	2612.5	2375
Total	3218.246	3102.05	2983.89	2749.53

4.3 Cost for Concrete Materials Production

The cost of concrete materials is presented in Table 4. These have been collected from the Saudi Arabian construction market. The table shows that the cost of concrete production materials that are made 100 % from natural aggregate is the cheapest concrete mix among other alternatives. The cost of concrete samples that are made from different percentages of recycled concrete aggregate is found to be much more expensive.

This difference between the cost of recycled and ordinary concrete alternatives is due to the variance between the cost of recycled concrete and natural aggregate, as the natural aggregate remains economically feasible. These results are contrary to other studies conducted in developing countries which found that the cost of recycled concrete aggregate is smaller than virgin aggregate [10] [11]. This can be explained by examining the Saudi Arabian construction market, where only locally produced aggregates are used. Furthermore, the cost of extracting and manufacturing the natural aggregates still have a low cost. The cost of manufacturing recycled aggregate remains expensive because this is not yet deployed in the local construction market.

Table 4 Cost of concrete materials based on the Saudi construction market

Data	NA	RA 25%	RA 50%	RA 100%
Natural aggregate cost 25 SAR/m^3	20	15	10	0
Sand cost 16.5 SAR/m^3	6.6	6.6	6.6	6.6
Portland cement cost kg/m^3	90	90	90	90
Concrete mixing cost SAR/ m^3	82	82	82	82
Water 9 SAR / m^3	1.4	1.4	1.4	1.4
Recycled aggregate cost 48 SAR /m^3	0	12	24	48
Total	200	207	214	228

5. CONCLUSION AND DISCUSSION

The experimental data extracted from this study indicate that the mechanical properties of proposed concrete mix design alternatives incorporating low percentages of recycled coarse aggregate were better than those with a high percentage of course aggregate. The increased percentage of recycled coarse aggregate led to a decrease in the strength of concrete that is represented by low values of compressive strength, split tensile strength, flexural strength, and high Schmidt hammer results. This result supports previous findings in other studies [7,8] and proves that using 25% recycled aggregate in concrete provides the best results compared with other percentages of recycled aggregate that were tested in this study.

Regarding the embodied energy that is used in the production of concrete, the results show that using recycled aggregate in manufacturing the concrete lead to decreasing embodied energy. The concrete mix alternatives with a high percentage of recycled aggregate have the lowest embodied energy values. These results can be justified because the energy used in materials transport differs between natural and recycled aggregate, as natural aggregate has to be extracted from remote areas which require more energy for materials transport to a concrete mixing plant, while the recycled aggregate production plant is usually located nearby to the concrete mixing plant which requires less energy for materials transport. In this study, the natural aggregate was transported from an area 100 km away, while the recycled aggregate production plant was 25 km away.

The cost of each concrete mix design alternative has been calculated based on data collocated from the Saudi Arabian construction market. The results show that the cost of concrete mix alternative (NA) that is made totally from natural aggregate has the lowest cost compared with others that are made with recycled concrete aggregate. The notable cost variance is obvious when comparing the NA and RA100% since there was a difference of 14% between them. This demonstrates that the recycled concrete is still not economically feasible when compared with traditional concrete. This is only when the cost calculation of each concrete mix alternative was based on the direct cost of constituent materials. However, the cost difference between them can be neglected if it takes into account the environmental impact of traditional concrete which is produced by the extraction of natural aggregates. Moreover, the government regulations that target the enhancement of the sustainability of the utilization of natural recourses is expected to increase the market price of natural aggregate through the application of a new tax on the extraction of natural aggregates, which will render recycled concrete more economically feasible.

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