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Experimental Study on Compressive Strength of Recycled Aggregate Concrete under High Temperature

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ABSTRACT

This research aims to study the effect of elevated temperature on the compressive strength evolution of concrete made with recycled aggregate. Demolished building concrete samples were collected from four different sites in Saudi Arabia, namely from Tabuk, Madina, Yanbu, and Riyadh. These concretes were crushed and recycled into aggregates to be used to make new concrete samples. These samples were tested for axial compressive strength at ages 3, 7, 14, and 28 days at ambient temperature. Samples of the same concrete mixes were subjected to the elevated temperature of 300°C and tested for compressive strength again. The experimental result reveals that the recycled aggregate concrete samples have good quality at ambient and elevated temperatures and are considered fairly close to the concrete made with natural aggregate. However, recycled aggregate concrete at high temperatures showed higher strength degradation than natural aggregate concrete, but with differences that do not exceed 5% to 10%. The concrete samples made from recycled coarse aggregates also reached the design strength. It can be considered acceptable, considering the high variation in the concrete's thermal response found in the literature.

KEYWORDS

Recycled coarse aggregate; compressive strength; strength evolution; high temperature

1 Introduction

Globally, solid waste generation of 3 billion tons every year with a continuously increasing trend was reported by [1]. In China, the Construction and Demolition Waste (CDW) reached 1.6 billion tons annually in 2016, of which the majority is considered demolished waste concrete [2]. Significant waste generation in the construction industry was reported around the globe, with an estimate of 850 to 880 Mt/year in the European Union (EU) [3,4], 317 Mt/year in the USA, and 77 Mt/year in Japan [5]. To approach the problem, the EU imposed targets for reducing, reuse, and recycling construction and demolition waste CDW, establishing that by 2020, 70% of the produced CDW must be recycled [4,6]. The Gulf Cooperation countries (GCC) rank in the world's top 10% of waste producers per capita [7]. The rapid population growth, development, and industrial development of municipal solid waste (MSW) production have significantly increased in the Kingdom of Saudi Arabia (KSA) to 15 million tons a year with an average rate of 1.4 kg per person per day, combined with industry and (CDW) [8,9]. The CDW



concerns in the KSA are on the rise at an alarming rate. For instance, Jeddah (KSA's second-largest city) generates 4.5–6.35 million tons of CDW annually, with 14% of the KSA population. In other KSA cities, such as Riyadh and Dammam, similar situations are present [10]. If sufficient consideration is not given to this form of waste, significant environmental, public health, and land area issues due to radiation and gas emissions will arise [11].

In the last two decades, billions of tons of demolished buildings waste have been generated worldwide. The main reason for generating such amounts of demolished waste is reaching the structure's end of life. Another reason for this could be the inadequate constructed structures. A building demolishing waste, recycled through reusing it as aggregate in concrete mixes, is a modern approach for reducing environmental pollution by reducing waste and conserving the aggregate natural reserve. It might also reduce the cost of new constructions in some cases even though the sources of good quality natural aggregate are considerably declining in some areas of the world. As a replacement for natural aggregate, the reuse of buildings waste is slowly implemented in the industry, despite large buildings' waste and significant changes in the available environmental regulations, such as the green building codes.

The recycled coarse aggregate has been used in the road industry for years but was implemented in buildings in limited cases. The experimental work carried out by [12] on replacing 100% recycled coarse aggregates in concrete found good strength characteristics. The study [13] on sustainable sand concrete made with recycled crushed fine aggregate showed good performance at an ambient and elevated temperature up to 300°C. Reference [14] discloses the effect of recycled aggregate on compressive strength at different exposure conditions, with 20% recycled aggregate and treated wastewater as mixing water. The study performed by [15] illustrates the effect of exposed temperatures of 0°C, 50°C, 100°C, 200°C, 300°C, and 400°C on recycled coarse aggregate concrete. Results reveal that at temperature ranges (300°C–400°C), a 55 percent reduction in strength was observed in all mixes on average. In new concrete, the utilization of recycled coarse aggregate is entirely satisfactory in compressive strength compared to natural coarse aggregates. Recycled coarse aggregate performance is found to be even better [16,17]. Considering the benefits of recycled aggregates, the European concrete standard EN 206:2013, annex E, and EN 13369:2012 firmly advise utilizing concrete with coarse recycled aggregates. It does come with a few flaws but with a considerable number of benefits [18].

Although studies related to the usage of recycled coarse aggregate in concrete are numerous, limited experimental studies were found on long-term durability and recycled aggregate concrete under extreme conditions. It has been found that a detailed physical analysis of recycled concrete materials is not reported extensively. Also, the effects of high temperature on concrete performance made of recycled coarse material are minimal.

2 Literature Review

Each year, ten to eleven billion tonnes of aggregate are being used all over the world. For example, approximately two billion tonnes of aggregate are produced and used in European Union countries per year [19]. Many researchers have studied recycled aggregate utilization in concrete mixes as an alternative to natural aggregate due to this high demand. Many studies have shown that concrete made with recycled aggregate may have mechanical properties similar to that made with conventional natural aggregate [20,21]. The recycled aggregate obtained from demolished concrete was angular, with a higher water absorption rate and higher specific gravity than natural coarse aggregate, and usually higher compressive strength [22]. In various construction activities, many previous research types were carried out using industrial wastes (i.e., fly ash, demolished waste, stone dust, crumb rubber powder, etc.) in various construction activities. Many technologies for recycling concrete wastes have been developed [23,24]. Reference [25] carried out a study to evaluate the influence of demolished waste aggregate on the mechanical properties of concrete. Reference [26] showed that recycled demolished concrete's

behavior with partial replacement of cement by recycled demolished waste is similar to conventional concrete. Reference [27] discussed the use of recycled coarse aggregate in concrete in a repeated fashion and investigated concrete's fresh and hardened properties. The study was primarily conducted to test the possibility of using aggregate obtained from crushed old concrete pavements in concrete manufacturing with supplementary cementitious materials. Replacement of natural coarse aggregate with recycled alternative extracted from the low-quality old concrete pavements obtained concrete with similar strength parameters. According to [28], no problem should exist in making concrete from recycled concrete derived from the construction industry, such as precast concrete or brick plants.

The various products are routinely made from the same type of concrete and, therefore, the problem of variability in the properties of the rubble should not exist. A reduction of up to 10% in the concrete compressive strength is reported when up to 10% of aggregate was replaced with recycled alternative crushed from old high-strength concrete. The replacement ratio strongly affects the properties of the new concrete, and a reduction of almost 20% was reported for a higher replacement ratio of 25%. Reference [29] reported similar properties of concretes in which coarse granite aggregate was replaced by crushed high-strength clay bricks (compressive strength of 153 MPa). Reference [30] investigated the influence of fine and coarse recycled concrete aggregate on the evolution of compressive strength. They replaced different percentages of natural aggregate with recycled ones, reaching 31% replacement. A review of recent works of using recycled aggregate concrete is done by [31].

The constituent materials' properties positively influence the structural concrete response to fire, mainly the type and aggregate source used. Reference [32] studied the performance of high-strength concrete under high temperatures, which can be different from regular strength concrete. Reference [33] formulated a mathematical model that couples the thermal and mechanical characteristics of concrete subjected to high temperatures, based on tests carried out on high performance and ultra-high-performance concretes. Generally, it is believed that high temperature causes significant physical and chemical changes in concrete, such as smaller pores and increased calcium carbonate content [34]. Reference [35] states that Calcium Hydroxide, one of the essential compounds in cement paste, dehydrates at around 550°C resulting in concrete shrinkage. Also, aggregate starts deteriorating significantly at that temperature. Reference [36] showed that the reduction in concrete's compressive strength was significantly more considerable for specimens exposed to temperatures higher than 600°C. Reference [37] also observed that the weight of the concrete reduced significantly at temperatures above 800°C. Reference [38] studied the effect of high temperatures on the strength evolution of concrete made with natural aggregate at different ages.

Not too many researches had investigated the behavior of recycled aggregate concrete at high temperatures. Reference [39] made a review about research carried out on concrete with recycled materials after exposure to fire. They could only list five types of research about recycled aggregate concrete at high temperatures. They recommended that more research is needed on this topic. Hence, the main goal of this research is to enhance the available limited knowledge concerning the compressive strength of concrete made with demolished concrete wastes as a substitute for natural aggregate under high temperatures. A systematic literature review in [Table 1](#) reported the past studies on sustainable concrete performance made by different waste materials subjected to elevated temperatures. However, limited studies were found on 100% recycled coarse aggregate concrete subjected to elevated temperatures. Other studies were reported in [Table 1](#) on sustainable concrete made by mixing other waste materials, providing a systematic relationship on concrete strength at elevated temperatures.

Table 1: Key findings of sustainable concrete made by recycled waste exposed to elevated temperatures

| Study | Mixing waste materials | Exposed temperatures | Key findings |
|-------|--|---|---|
| [15] | Recycled aggregate | 0°C, 50°C, 100°C, 200°C, 300°C, and 400°C | <p>i. The average reduction of about 38% was found in all percentage replacements with recycled aggregate in sustainable concrete with exposed temperatures ranging up to 200°C.</p> <p>ii. At 100% replacement of natural aggregate by recycled observed 25% reduction in strength.</p> <p>iii. An average of 55% reduction in strength was seen in the temperature ranges (300–400°C) in all mixes.</p> |
| [40] | Fly ash, spent foundry sand | 27°C, 100°C, 200°C, and 300°C | <p>i. At the exposed temperature between (27–200°C), a slight loss of strength was observed.</p> <p>ii. Test results show the enhancement in compressive strength in the temperature ranges (200–300°C) compared to (27–200°C).</p> <p>iii. It has also been observed that the residual compressive strength increases between (200–300°C)</p> |
| [41] | Recycled aggregate, glass powder, marble powder, and rice husk ash | 25°C, 200°C, 400°C, and 600°C | <p>i. The residual compression strength of recycled aggregate concrete was satisfactory and equivalent results compared to the control sample at elevated temperatures.</p> <p>ii. The compressive strength of recycled aggregate concrete decreased pattern at any given exposure temperature, increasing the recycled aggregate percentage.</p> <p>iii. Improvement in both compressive and splitting tensile strengths was reported at 20% cement replacement by glass powder in 100% recycled aggregate concrete in all exposure temperatures.</p> |
| [42] | Recycled coarse aggregate, silica fume | 200°C, 400°C, 600°C, and 800°C | <p>i. The pure recycled aggregates concrete demonstrates low fracture resistance at high temperatures. The addition of fine steel fibers significantly enhances the recycled aggregates concrete fracture efficiency at various high temperatures.</p> <p>ii. With silica fume's addition, the fracture properties of steel-fiber recycled aggregates concrete are nonlinearly subjected to elevated temperatures.</p> <p>iii. With a temperature reaching more than 200°C, silica fume's influence on flexural strength, fracture energy, and fracture toughness increases and decreases with increasing silica fume content in the mixes.</p> |

(Continued)

| Table 1 (continued). | | | |
|-----------------------------|---|--|---|
| Study | Mixing waste materials | Exposed temperatures | Key findings |
| [43] | Recycled coarse aggregate, crumb rubber | 25°C, 200°C, 400°C, 600°C | <p>i. After exposure to 200°C, rubber crumb and steel fiber reinforced recycled aggregate concrete (RSRAC) retained 84.30% of their compressive strength.</p> <p>ii. At the elevated temperature of 400°C and 600°C compressive strength was reduced to 49.66% and 24.77%, respectively.</p> <p>iii. The effects of high temperatures on the (RSRAC) mixes' damage mechanism and how the crumb rubber's inclusion contributes to alleviating the damage should be further studied by examining the change in concrete microstructures in the future.</p> |
| [44] | Recycled concrete aggregate | 20°C, 150°C 300°C, 450°C, 600°C | <p>i. Samples led to collapse while temperatures were increasing more than 450°C.</p> <p>ii. The maximum heating degree could be considered as 450°C. It is because by increasing the temperature, the pore water pressure rises and dissipates.</p> <p>iii. The maximum 1% crumb rubber would be suggested with recycled concrete aggregate; as per the test analysis, composition reported the highest strength compared to other mixes.</p> |
| [45] | Recycled crushed stone aggregates and rubber powder | 20°C, 200°C, 400°C, 600°C | <p>i. The results indicate that after exposure to a temperature of 200°C, the strength of the recycled aggregate concrete specimens decreased by approximately 23% and 31% for the cubes and cylinders.</p> <p>ii. Rubber in the concrete decomposed at 400°C and decreased the compressive strength. Moreover, rubber-modified recycled aggregate concrete (RRAC) has dramatically reduced its compressive strength at 600°C.</p> <p>iii. The addition of rubber particles improved the recycled aggregate concrete's cracking resistance after exposure to high temperatures.</p> <p>iv. Based on the results, a rubber content of 4% is recommended. A ratio of approximately 4% presented the best fire resistance performance under compressive loads.</p> |
| [46] | Waste foundry sand | 300°C, 400°C, 500°C, 600°C, 700°C, 800°C | <p>i. The residual compressive strength decreases with increasing temperature.</p> <p>ii. The residual compressive strength of the concrete containing waste foundry sand as a partial replacement of natural sand at ambient temperature after exposure to 300, 400, 500, 600, 700 and 800°C was reduced in the range of 29.00% to 32.5%, 38.5% to 42.5%, 48.5% to 51.00%, 59.00% to 62.00%, 65.00% to 69.00%, and 68.5% to 74%.</p> |

3 Methodology

The present study collected demolished wastes from four different Saudi Arabia cities: Tabuk, Madina, Yanbu, and Riyadh. All demolished structures used in the study were commercial cum residential buildings, and the ages of buildings were estimated in the range of 20 to 25 years, where no written records were found in sites. Then, concrete cores were taken from these samples and tested for compressive strength. Besides, enough amounts of this old concrete were crushed to be used as aggregate for new concrete mixes. Physical properties were calculated for recycled aggregate since they are necessary for preparing the new concrete mixes. A control concrete sample of 100% natural coarse aggregate concrete has also been made. The design strength of all concrete mixes is 30 MPa, and the target strength is 38.5 MPa. The mixes were prepared by the absolute volume method. These prepared concrete samples were tested for axial compressive strength at 3, 7, 14, and 28 days at ambient temperature and elevated temperature of 300°C.

4 Sample Preparation of Samples

4.1 Concrete Coring and Testing

Concrete cores are considered a semi-destructive method and are used to determine the strength of structures, such as the compressive strength, splitting tensile strength, and flexural strength of in-situ concrete. Selected samples from demolished buildings concrete from four cities mentioned earlier above were brought to Tabuk city. Core drill and saw were then used for drilling cores from specimens (Fig. 1). The coring process was conducted at Independent Testing Laboratories of Soil and Foundation, Ltd., Co (Safco), Tabuk, Saudi Arabia. The coring process was done according to (ASTM-C-42/C-42 M-04, 2004) standards [47]. The extracted cores were thoroughly inspected for cracks, delamination, deterioration, seepage, and corrosion. Three cuts have been made for each city sample.



Figure 1: (a) Concrete core sample drilling and (b) samples after testing

Table 1 reports the dimensions of these cores. The core samples have different diameters because the demolished concrete collected from the different cities was not always big enough to take large cores. Core samples were then tested for uniaxial compressive strength, and compressive strength results are also reported in Table 2. The acceptance criteria for core strength are to be established by the tester. Due to many factors, like the drilling process's destructive nature, core strength is less than the independent cast samples' strength. Some of the energy used to cut the samples could cause micro-cracks and bond weakening between cement matrix to aggregate surface in the core. The core test results are usually affected by many factors, such as the location of cores, orientation of cores, and the in-place temperature and moisture history. Hence, codes usually make corrections to core strength. According to the [48], the core test result can be used to calculate the in-place concrete strength using the formula:

$$f_c = F_{l/d} F_{dia} F_{mc} F_d f_{core} \quad (1)$$

where f_c is the equivalent in-place strength of demolished concrete samples.

Table 2: Cores tests data

| Sample No. | Length before capping (mm) | Length after capping (mm) | Average diameter (mm) | Uncorrected failure load (kN) | Uncorrected stress (MPa) | Diameter factor F_{dia} | length-to-diameter ratio factor $F_{l/d}$ | Equivalent in-place strength f_c | Average in-place strength |
|------------|----------------------------|---------------------------|-----------------------|-------------------------------|--------------------------|---------------------------|---|------------------------------------|---------------------------|
| Tabuk 1 | 112.0 | 115.0 | 69.00 | 113.74 | 30.42 | 1.025 | 0.987 | 32.62 | 33.88 |
| Tabuk 2 | 112.0 | 115.0 | 69.00 | 123.77 | 33.10 | 1.025 | 0.987 | 35.50 | |
| Tabuk 3 | 112.0 | 115.0 | 69.00 | 116.9 | 31.26 | 1.025 | 0.987 | 33.53 | |
| Madina 1 | 89.0 | 92.2 | 69.00 | 124.24 | 33.23 | 1.025 | 0.949 | 34.26 | 30.71 |
| Madina 2 | 96.0 | 99.0 | 69.00 | 96.15 | 25.71 | 1.025 | 0.962 | 26.88 | |
| Madina 3 | 90.0 | 93.0 | 69.00 | 112.21 | 30.01 | 1.025 | 0.950 | 30.98 | |
| Yanbu 1 | 90.0 | 102.0 | 94.00 | 217.1 | 31.28 | 1.007 | 0.902 | 30.13 | 29.34 |
| Yanbu 2 | 100.0 | 112.0 | 94.00 | 222.4 | 32.05 | 1.007 | 0.924 | 31.61 | |
| Yanbu 3 | 40.0 | 52.0 | 94.00 | 225.7 | 32.52 | 1.007 | 0.757 | 26.28 | |
| Riyadh 1 | 148.5 | 154.0 | 99.60 | 257 | 32.99 | 1.00 | 0.976 | 34.13 | 31.59 |
| Riyadh 2 | 138.5 | 145.0 | 99.60 | 216 | 27.72 | 1.00 | 0.965 | 28.36 | |
| Riyadh 3 | 158.3 | 163.0 | 99.60 | 241 | 30.93 | 1.00 | 0.985 | 32.28 | |

f_{core} : is the core strength.

F_{dia} : diameter factor equals 1.06, 1.00, and 0.98 for a diameter of 50 mm, 100 mm, and 150 mm, respectively.

F_{mc} : Moisture condition factor, taken as 1 if standard treatment is followed.

F_d : Factor of damage sustained during drilling, including microcracking, which equals 1.06.

$F_{l/d}$: length-to-diameter ratio factor, can be calculated from the equation:

$$F_{l/d} = 1 - \{0.130 - 0.00043f_{core}\} \left(2 - \frac{l}{d}\right)^2 \quad (2)$$

where l is the capped length of the core, d is the diameter of the core. These formulae are used to obtain the equivalent in-place strength, which is presented in Table 2.

The average equivalent in-place concrete strength ranges from 29.34 MPa (Yanbu samples) to 33.88 MPa (Tabuk samples). Assuming these concretes' target strength was 28 MPa or 30 MPa, which is a common practice in these cities, these core samples are considered achieving the standards, which requires the average strength of cores to be higher than 85% of specified strength (25.5 MPa). No individual sample is less than 75% of specified strength (22.5 MPa). It shall be noted that Yanbu city, which has the lowest core strength, is very humid, especially in the summer semester. Madina and Riyadh cities suffer high temperatures in the summer, but without humidity like that in Yanbu. Among the four cities, Tabuk has the most moderate climate. It could affect the strength of the concrete samples collected from these cities, but unfortunately, this cannot be determined since these concretes were made independently.

4.2 Recycling Concrete into Aggregate

Demolished concrete obtained from the four cities was crushed into coarse aggregate. The specific gravity, water absorption rate, fineness modulus, bulk density, crushing value, and abrasion resistance for these aggregates were measured to compare these recycled aggregate physical properties with natural aggregate. The physical properties of natural and recycled aggregate are listed in Table 3. Specific gravity for the recycled aggregate is

very close to that of the natural aggregate. Water absorption is much higher for recycled aggregate (around 7% to 8.7%) than natural aggregate (around 1%). It should be taken into account when design concrete mix is prepared for recycled aggregate. The fineness modulus shows no significant differences between samples. Bulk density also shows no significant differences, except for Madina concrete, which is significantly lower than the others. Also, Madina concrete aggregate shows a higher crushing value of 19% than other samples (between 8% and 11%). Abrasion resistance for all recycled aggregate samples is close to each other (between 20.7% and 22.4%) and slightly higher than natural aggregate (17.1%).

Table 3: Physical properties of natural and recycled aggregate

| Properties | Natural aggregate | Tabuk | Madina | Yanbu | Riyadh |
|------------------------------------|-------------------|-------|--------|-------|--------|
| Specific gravity | 2.806 | 2.695 | 2.720 | 2.788 | 2.722 |
| Water absorption (%) | 0.958 | 7.240 | 6.955 | 8.688 | 7.312 |
| Fineness modulus | 7.680 | 7.880 | 8.668 | 9.535 | 7.958 |
| Bulk density (ton/m ³) | 2.833 | 2.748 | 2.440 | 2.800 | 2.775 |
| Crushing value (%) | 8.0 | 9.0 | 19.0 | 11.0 | 8.9 |
| Abrasion resistance (%) | 17.10 | 22.20 | 20.720 | 22.50 | 22.422 |

Besides, sieve analysis was done for the recycled aggregate and the natural aggregate. The results of particle distribution are plotted in Fig. 2. The distribution shows that Madina, Yanbu, and Riyadh aggregate distribution is identical, and the three of them are a bit coarser than Tabuk aggregate. All four samples of recycled aggregate are also a bit more courses than natural aggregate particle distribution. However, the differences can be considered negligible. The distributions are well graded, covering all significant sizes for the concrete mix, with no size gaps, which is considered acceptable.

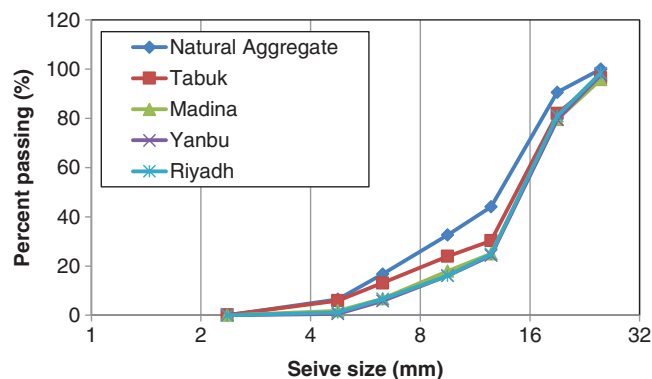


Figure 2: Particle size distribution of aggregate samples

4.3 New Concrete Samples

The recycled aggregate was used as a coarse aggregate to produce new concrete mixes, compared with natural aggregate concrete. The target strength is to produce 38 MPa concrete after 28 days of curing. Locally available ordinary Portland cement (Type 1) was used in all samples. Fine dune sand is used as fine aggregate in the mixes for both natural and recycled aggregate concrete. No fine recycled aggregate was used in this study. Any impurities in both fine and coarse aggregate were removed by screening, sieving, and washing. Recycled aggregate with a diameter of less than 5 mm was discarded. No admixtures or additives were used in the study.

Five concrete mixes were prepared, four from recycled aggregate and one with natural aggregate to serve as a reference sample. The absolute volume method was used to prepare the design mix proportions for target characteristic compressive strength of 38 MPa. The mix proportions are: 460 kg/m³ cement, 762 kg/m³ fine aggregate, 1056 kg/m³ coarse aggregate, and 216 kg/m³ water. Aggregate sizes of 19 mm, 12.5 mm, and 9.5 mm were used in the mixes. Demolished ones replaced only coarse aggregate with a volumetric replacement ratio of 1(9.5 mm): 2(12.5 mm): 3(19 mm). To substitute for the high-water absorption of recycled aggregate, about 8% extra water was used in the recycled aggregate concrete mixes. Concrete cylinders having 75 mm diameter and 150 mm height were prepared from these mixes.

5 Results and Discussion

Specimens were tested at normal room temperature to evaluate concrete's compressive strength at 3, 7, 14, and 28 days after casting. The test results are shown in Fig. 3, along with the results of the core tests. Samples of Tabuk aggregate showed the highest final strength (about 45.6 MPa) at 28 days, which is expected because the core tests also showed the strongest recycled aggregate. It is noticed that Madina's new concrete mix achieved about 40 MPa, which is about 12% less than other samples. The different things about Madina aggregate compared with other cities samples are the higher crushing value and lower density, which could mean less quality materials, which could be the reason for this discrepancy. So, the core test cannot be considered a good initial indicator for the new concrete mixes' final strength. One interesting notice is that the early strength at 3 days for Tabuk, Yanbu, and Riyadh samples (32 MPa, 32.5 MPa, and 31.7 MPa, respectively) was significantly higher than the natural aggregate sample (29.5 MPa). It could indicate an expedited chemical reaction and strength gain in recycled concrete mixes. Only Madina's sample strength was less than natural aggregate sample strength, but at all ages and not only at an early age. It can be attributed to the high bonding strength between the recycled coarse aggregate and surrounding paste due to the recycled aggregate's angularity and the residual cementation on the demolished aggregate's surface. The deviation of test results is also represented in the Figure and is considered acceptable.

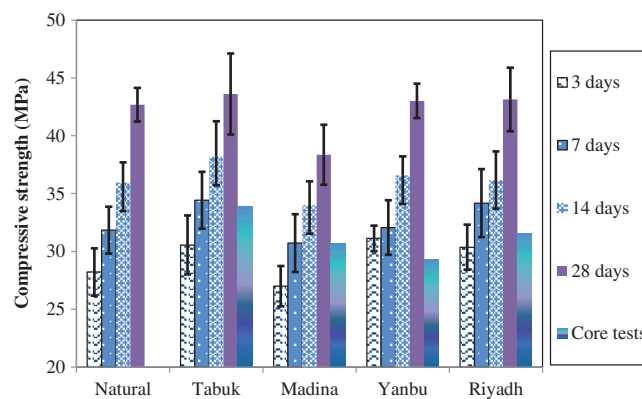


Figure 3: Concrete strength with natural and recycled aggregate at ambient temperature

The high temperature usually causes aggregate damage; weakening of the cement paste-aggregate bond; weakening of the cement paste due to increased porosity on dehydration; the partial breakdown of the calcium silicate hydrate (the main product of cement hydration), and development of cracking.

Samples from the same previous concrete mixes were thermally treated. They were subjected to a temperature of 300°C for two hours and then left to cool down. The next day they were tested for compressive strength. The results are illustrated in Fig. 4. It can be seen that all recycled aggregate

concrete mixes show lower residual strength compared with a natural aggregate mix, after thermal loading, at all ages. It is expected since recycled aggregate mixes contain more cement content (from original crushed concrete) than natural aggregate mixes. Cement is the binding material in concrete, and it is more susceptible to damage due to high degrees of temperatures than natural aggregate particles. Unlike the samples tested at room temperature, which showed higher early strength (at 3 days) in recycled aggregate mixes, high temperature retards the early strength gain in recycled aggregate mixes compared with a natural aggregate mix.

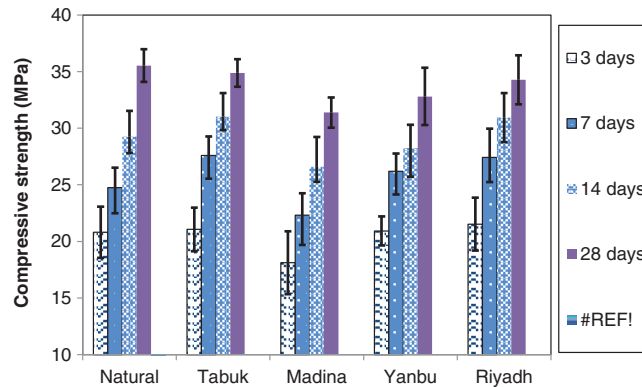


Figure 4: Concrete strength with natural and recycled aggregate at 300°C temperature

Fig. 5 shows the loss in concrete compressive strength at different ages due to 300°C temperature. For both recycled aggregate and natural aggregate mixes, it is seen that the loss percentage in strength is higher at early stages, ranging between about 27% and 33% loss in strength at 3 days. The loss decreases with increasing age. At age 28 days, the loss is 17% to 24%. Similar behavior was seen by [38], but they only used natural aggregate.

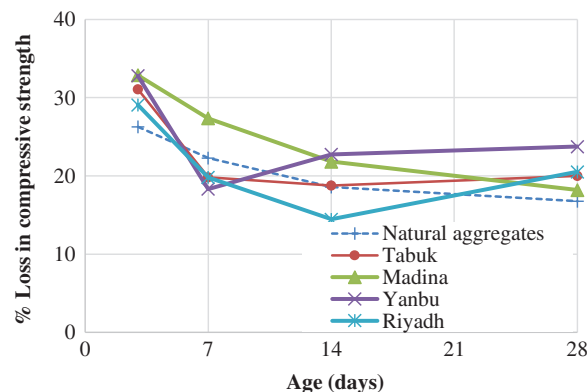


Figure 5: Loss in concrete compressive strength at different ages due to 300°C temperature

Fig. 6 shows the effect of high temperatures on concrete compressive strength. References [49] and [50] collected so much experimental data in various research for natural aggregate concrete mixes and set an upper and lower limit for these data. These limits are presented in the Figure. Limits in [49] are a bit lower than the limits of [50], but the difference is acceptable. As shown, current study results lie within limits. In addition, they are above the mean of the experimentally collected data [49]. The design curve for natural carbonate aggregate concrete, with the unstressed sample extracted from (ACI-216.1 M-07)

[51], is also drawn in the Figure, along with the curve from (EN1992 Eurocode 2) [52]. Current study results are also above the ACI design curve. Although all current samples comply with ACI requirements, the recycled aggregate samples suffer higher degradation in strength (5% to 10% less strength than a natural aggregate mix). This indicates that recycled aggregate concrete under high temperatures should be used with caution if prepared using code design curves. However, Eurocode only allows a 10% reduction in compressive strength at 300°C, so current samples do not comply with Eurocode.

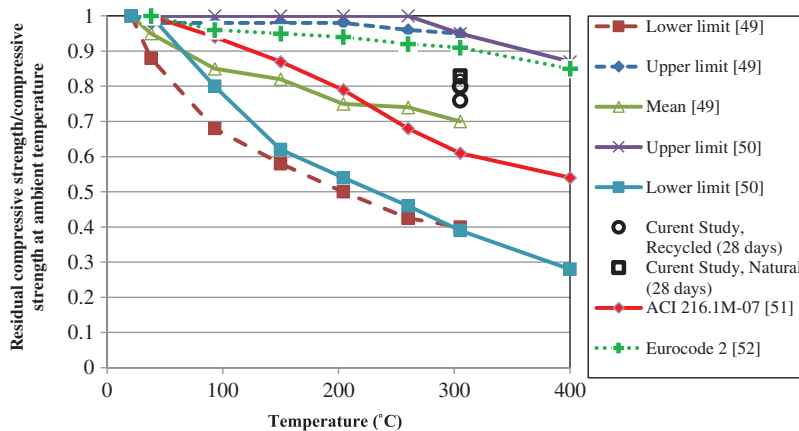


Figure 6: Effect of temperature on concrete compressive strength

6 Conclusions

This study replaced 100% natural coarse aggregate with recycled coarse aggregate made from old concrete, collected from four different sites. The compressive strength of concrete samples made from natural coarse aggregate and recycled coarse aggregate were evaluated at ambient and elevated temperatures of 300°C. Based on the test results and discussions, the following conclusions are made:

1. Compared with natural aggregates, a high-water absorption rate is found for recycled aggregate, which should be substituted in the design mix.
2. The recycled aggregate's high crushing value and abrasion resistance can be a good indicator of final lower strength concrete.
3. The evolution of strength in recycled aggregate concrete is similar to natural aggregate concrete at ambient temperature.
4. When subjected to elevated temperature, substantial losses are noticed in high percentage in the early age of concrete, which is more prominent in recycled aggregate concrete than natural aggregate concrete. At the late age of concrete, the percent loss in concrete strength due to high temperature becomes lower than at an early age. However still, recycled aggregate concrete has a higher loss compared with natural aggregate concrete.
5. Current study samples comply with ACI code requirements but fail to comply with Eurocode requirements. It shows high differences between the requirements of different codes for concrete under high temperatures.
6. Compared with normal aggregate concrete, recycled aggregate concrete shows good resistance to strength degradation due to thermal loading, which is only 5% to 10% lower than natural aggregate concrete.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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