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ScienceDirect

Procedia Engineering 145 (2016) 1518 – 1525

Procedia Engineering

www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

# Recycled Construction Debris as Concrete Aggregate for Sustainable Construction Materials

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**Abstract**

An experimental program was conducted in order to compare the engineering properties of reclaimed concrete aggregate waste from various demolition sources: lab-tested concrete waste from a commercial ready-mix company with known engineering properties, construction and demolition (C&D) concrete waste with some information about engineering properties, and regular aggregate from the market, which was used as control samples. This study explores the potential use of construction waste for the development of sustainable construction materials in order to obtain economic returns from the waste. After processing the construction debris into gravel, the amount of reclaimed material from the waste was calculated, and then aggregate tests were conducted. Lab samples were fabricated based on a 35 MPa mix-design with reclaimed aggregate from the various waste sources, along with control samples. Finally, compressive strength, tensile strength, and flexural strength, as well as some non-destructive tests (NDT), such as pulse velocity and hammer tests, were conducted. Correlation between results obtained from the various tests were analyzed in this experimental program; a linear correlation was noted between compressive strength and other mechanical properties evaluated, namely, split tensile strength, flexural strength, pulse velocity, and Schmidt Hammer.


Peer-review under responsibility of the organizing committee of ICSDEC 2016

*Keywords:* sustainable concrete design, recycling aggregates, construction and demolition concrete, concrete engineering properties

## 1. Introduction

Management of solid waste is a serious challenge faced globally; however, it is a particular problem in the gulf region, where most countries have the highest per capita waste generation in the world [1]. Industrial growth, construction booms, rapid urbanization, changing lifestyles, and unsustainable consumption patterns, have all contributed to this growing waste problem. Accelerated urbanization has led to the spending of billions on

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Peer-review under responsibility of the organizing committee of ICSDEC 2016
doi:10.1016/j.proeng.2016.04.191

construction for infrastructure and public sector building programs, which has resulted in an increasing need for construction materials and the management of related construction wastes. After demolition of old roads and buildings, tons of construction waste are discarded; the removed concrete is also often considered worthless and disposed of as demolition waste [2]. The majority of construction waste, however, is considered inert and can potentially be used for recycled construction materials.

Natural resources are generally consumed by the construction sector in substantial amounts, which is producing significant quantities of construction and demolition (C&D) waste. C&D waste constitutes the largest volume of all solid waste [3]. For instance, the U.S. construction industry generates over 100 million tons of C&D waste per year [4], and approximately 29% of the solid waste stream in the U.S. is created by the construction sector [5]. In addition, C&D waste contributes more than 50% of all landfill volume in the UK [6], and 70 million tons of C&D waste is discarded each year [7]. Craven *et al*. 1994 [8] have reported that construction activities generated approximately 20–30% of all waste in Australia, which was disposed of in landfills. The annual generation of C&D waste in Hong Kong, between 1993 and 2004, doubled, reaching 20 million tons in 2004 [9]. Nearly 23% of the solid waste in Hong Kong comes from construction sector activities [10]. The massive amount of construction waste in different countries has revealed the importance of local action in order to manage, recycle and re-use the waste generated throughout the lifecycle of concrete infrastructure [3].

Construction waste generation and the unsustainable use of depleting natural resources for building materials are also linked to the adverse environmental impacts of the construction industry. Globally, it is estimated that approximately 10-30% of waste disposed of in landfills originates from construction and demolition activities [11]. Moreover, the excessive use of natural resources, such as blast-mountain rock for gravel production, has become an increasing environmental concern, which needs to be addressed in order to create awareness, and to develop sustainable integrated management programs and suitable recycling processes in order to gain economic returns from these wastes [1].

According to Green Middle East [12], countries that are part of the Gulf Cooperation Council (GCC) produce nearly 80 million tons of waste annually, 53% of which is construction and demolition waste, 33% is municipal solid waste and 14% industrial waste. Other estimates put the current total volume of solid waste generated in the GCC region at around 120 million tons per year [13]. This indicates that the generation of solid waste is rising rapidly. Infrastructure improvements and modernization are also resulting in the production of large amounts of demolition waste. Consequently, the scale of the challenges faced by waste management sectors in the gulf region is even larger. The development of waste management approaches and infrastructure, therefore, needs to keep up with the pace of waste generation.

Construction waste in the Kingdom of Saudi Arabia consists of solid debris that comes from excavation and construction, including pieces of used concrete, marble, plastic, petrochemicals, papers, asphalt, paint products, gravel and small pieces of steel that cannot be detached from waste concrete. In a dump site east of Jeddah, construction waste was found to contain big pieces of marble, gypsum, ceiling boards and ceramics, which could be reused without having to be recycled. It is estimated that more than half of the solid waste in the Gulf region comes from construction sites, and since Saudi Arabia is the biggest country in the Gulf, it is also considered to be the largest contributor to solid waste in the Gulf.

The Saudi Arabian construction sector is booming because of increased revenue from oil, and its government spending has led the way with the implementation of ambitious development plans for infrastructure [14]. This has consequently led to increases in demands for raw construction materials, such as aggregate and sand from local sources, which are utilized in construction projects. Moreover, other GCC countries, such as Qatar, import raw construction materials, such as aggregate, from Saudi Arabia as well [15]. This massive degradation of Saudi natural resources has led to the need to find alternative sources for construction materials in order to minimize raw material input and to relieve the pressure on natural resources. Recycled demolished building materials, such as concrete, can be considered as an alternative source of coarse aggregate for the production of new concrete, and has the potential to help reduce the depletion of natural resources for aggregate [16]. 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 resulting from the demolition of older buildings under the current boom in infrastructure development and urban planning in most Saudi cities. Husain and Assas [17] emphasized the promotion of using recycled materials as an urgent requirement in the present situation of the Saudi construction industry. They argued that recycling construction waste would not only preserve natural resources, but would also support safety and economy in the construction of infrastructure. Although some attempts have been made to study the effects of silica fume on the characteristics of recycled concrete aggregate [18], further research is necessary in order to determine the feasibility of using recycled aggregate material in the construction industry in Saudi Arabia.

Through the development of sustainable construction materials, and mandatory waste disposal regulations, environmental goals can be achieved. There is a great need for developing suitable recycling processes to protect the environment, as well as to gain economic returns from the waste. Increasing the recycling and reuse of C&D waste within the industry will help conserve dwindling natural resources [1]. There are growing interests in many parts of the world in recycling and reusing C&D waste by the construction industry. Netherland has the highest rate of recycling construction waste, at 93%, followed by Turkey, where effective waste management has enabled recovery of almost 90% of C&D waste [19]. Australia has achieved 87% C&D waste recycling [20], followed by Denmark at 82% [21], and Germany at 18% [22]. The total C&D waste for England in 2008 was estimated at 86.9 million tons, of which 53 million tons were recycled and a further 11 million tons were spread on exempt sites, for land reclamation, agricultural improvement, or infrastructure projects [23].

Reuse and recycling of concrete waste, which constitutes the largest proportion of C&D waste, offers both a solution to waste disposal problems and enables preservation of natural resources. While 40% of globally used rocks, pebbles, stones, and sand are consumed in infrastructure activities each year, the availability of good quality aggregate is decreasing [24]. In addition, European Union members produce approximately 50 million tons of concrete waste each year, compared with 60 million tons in the US, and 10-12 million tons in Japan. Japan has reduced the use of aggregates by 2.5 million $m^3$ by recycling concrete wastes from ready-mix concrete plants [25].

## 2. Case Studies

This study considers case studies from two different sources, so that the suitability for recycled waste materials can be determined easily. For case study 1, a ten-year-old single storey mosque (Fig 1(a)) was considered, from which demolished structural elements, such as beams and columns, with known engineering properties of compressive strength, etc., were obtained. For case study 2, randomly chosen demolished structural elements obtained from a municipal dumpsite were considered without any prior knowledge about the engineering properties of the concrete waste (Figure 1(b)).

(a) 

(b) 

Fig. 1 (a): Ten-year-old concrete structure of a single story mosque; (b) Random concrete waste from construction and demolition.

## 3. Experimental Program

### *3.1 Specimen Preparation and Aggregate Engineering Properties*

An experimental program was conducted in order to compare the engineering properties of aggregate obtained from reclaimed concrete waste from different sources: construction and demolition (C&D) concrete waste with and without some prior information, lab-tested concrete waste from a commercial ready-mix company with known engineering properties, and regular aggregate from the market. After processing the concrete waste into gravel with a crusher, the amount of reclaimed material from the waste was calculated; the reclaimed gravel was then processed through an abrasion machine (Figure 2). It was found that from 100 kg of demolished concrete waste, 30 kg of quality recycled aggregate can be obtained.

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. The lab samples were fabricated based-on a 35 MPa mix-design with the various recycled aggregate waste, along with control samples fabricated with aggregate from the market. Finally, compressive strength, tensile strength, and flexural strength tests, along with some non-destructive tests (NDT), such as plus velocity and Schmidt hammer, were conducted. Correlations between results obtained from the various tests were calculated in this experimental program.

Fig 2: Processing construction debris into gravel.

### *3.1.1. Bulk Density (Unit Weight) and Voids*

Based on the specifications of ASTM C29/C29M – 09, the results obtained show that the bulk densities of the lab-tested concrete waste and C&D concrete waste were higher than the control sample, whereas the number of voids was less (see Table 1). This is due to the angularity of the aggregates, since a crusher machine was used to create a uniform aggregate size of 15 mm. The size, shape, and arrangement of the voids affect important engineering properties, such as compressive strength.

### *3.1.2 Relative Density (Specific Gravity), Absorption, and Resistance to Degradation*

According to ASTM C127 for specific gravity and absorption test, the nominal maximum size (9.5 mm) was used. The results show that the specific gravity increases as the absorption decreases (see Table 1).

Table 1: Physical Properties of aggregate from different sources

| Physical properties | C&D concrete waste | | Lab-tested concrete waste | Control sample |
|---|---|---|---|---|
| | Case 1 | Case 2 | | |
| Volume of Cylinder (m3) | 0.0053 | 0.0053 | 0.0053 | 0.0053 |
| Unit weight (kg/m3) - ASTM C29 / C29M - 09 | 1484.53 | 1361.51 | 1545.28 | 1478.11 |
| Voids (%) - ASTM C29 / C29M - 09 | 29.5 | 35.5 | 28.7 | 34.5 |
| Bulk specific gravity (SD) - ASTM C127 - 15 | 2.11 | 2.418 | 2.17 | 2.425 |
| Bulk specific gravity (SSD) - ASTM C127 - 15 | 2.2 | 2.461 | 2.24 | 2.467 |
| Apparent specific gravity - ASTM C127 - 15 | 2.32 | 2.527 | 2.32 | 2.531 |
| Water Absorption (%) - ASTM C127 - 15 | 4.32 | 1.78 | 2.86 | 1.73 |
| Loss by abrasion and impact (%) - ASTM C131-06 / ASTM C136 | 31% | 28% | 24.34% | 25% |

The specific gravity of the crushed recycled aggregate was lower than that of the otherwise identical regular aggregate, which is usually around 2.2 to 2.5 in the saturated surface-dry (SSD) condition. Due to the cement mortar attached to the particles, the absorption of recycled aggregate is much higher than that of the similar virgin aggregate, which is typically 2% to 6% for coarse aggregate; the results are suitable and fall within an acceptable range. A possible reason for the high absorption rate of the lab-tested and the C&D waste is a higher water-cement ratio used in the mix; when the water evaporates, it leaves behind voids that occupy space in the concrete.

## 4. Results

### *4.1 Compressive Strength (ASTM C109/C109M – 13)*

Three concrete specimens were prepared with the aggregate from each of the different sources: C&D concrete waste, lab-tested concrete waste, and regular aggregate from the market, which was used to prepare the control samples. All specimens were designed with a compressive strength of 35 MPa. The compressive strength of each specimen (see Table 2) was tested according to ASTM C109/C109M – 13, at 7, 14, and 28 days. The results indicate that, at 28 days, the control samples exceeded the design strength of 35 MPa, and have the highest strength; the specimens made from lab-tested waste aggregate and C&D waste aggregate from Case 1, which was taken from beams and columns, achieved the design strength, whereas the specimens made from aggregate from Case 2, taken from random concrete waste, was slightly below the design strength.

Table 2: Average Compressive strength (MPa) of three specimens for each aggregate source - ASTM C109/C109M – 13

| Curing time (Days) | C&D concrete waste | | Lab-tested concrete waste | Control sample |
|---|---|---|---|---|
| | Case 1 | Case 2 | | |
| 7 | 32.000 | 30.713 | 31.000 | 34.000 |
| 14 | 34.000 | 31.963 | 34.000 | 35.000 |
| 28 | 38.000 | 33.453 | 35.000 | 41.000 |

### *4.2 Tensile Strength (ATSM C496/C496M-11)*

The split tensile strength test was used to compare concrete made with aggregate from lab-tested concrete waste, construction and demolition (C&D) concrete waste, and regular aggregate from the market. Three specimens for each source were tested at 7, 14, and 28 days (see Table 3). The split tensile strength of the concrete specimens made with the market aggregate was generally higher than the strength of the specimens made with the lab-tested aggregate, especially at 28 days. Furthermore, the split tensile strength of the specimens made with the C&D concrete waste aggregate from Case 1 was also generally slightly higher than the strength of the specimens made with aggregate from Case 2 at 28 days.

Table 3: Average split tensile strength (MPa) of three specimens for each aggregate source - ATSM C496/C496M-11

| Curing time (Days) | C&D concrete waste | | Lab-tested concrete waste | Control sample |
|---|---|---|---|---|
| | Case 1 | Case 2 | | |
| 7 | 2.071 | 1.996 | 2.469 | 2.343 |
| 14 | 2.207 | 2.019 | 2.757 | 2.807 |
| 28 | 2.503 | 2.277 | 2.916 | 3.185 |

### *4.3 Flexural Strength (ASTM C78/C78M – 10)*

The flexural strength test was employed to compare the strength of concrete made with aggregate from the various sources. Three specimens for each source were tested at 7, 14, and 28 days (see Table 4).

Table 4: Flexural strength (MPa) of three specimens for each aggregate source - ASTM C78/C78M – 10e1

| Curing time (Days) | C&D concrete waste | | Lab-tested concrete waste | Control sample |
|---|---|---|---|---|
| | Case 1 | Case 2 | | |
| 7 | 2.019 | 1.917 | 2.251 | 2.571 |
| 14 | 2.945 | 2.668 | 2.847 | 3.589 |

| | | | | |
|---|---|---|---|---|
| 28 | 3.513 | 3.479 | 3.912 | 4.310 |

The flexural strength of the specimens for the market aggregate was higher overall than the specimens for all other aggregate sources; the lab-tested aggregate specimens had higher flexural strength values than the C&D aggregate. Between the C&D aggregate specimens, Case 1 had slightly higher flexural strength on average than the Case 2 specimens.

### *4.4 Schmidt hammer and Pulse velocity*

The Schmidt hammer test was used to test concrete specimens made with aggregate from the lab-tested concrete waste, construction and demolition (C&D) concrete waste, and regular aggregate from the market. Three specimens were fabricated for each aggregate source and then tested (see Table 5). The control samples made with market aggregate had the lowest values from 7 to 28 days, the lab-tested aggregate had lower values than the C&D aggregate, and between the two types of C&D aggregate, the Case 1 aggregate had lower values than the Case 2 aggregate specimens.

Table 5: Schmidt hammer ( Rebound Number) of three specimens for each aggregate source

| Curing time (Days) | C&D concrete waste | | Lab-tested concrete waste | Control sample |
|---|---|---|---|---|
| | Case 1 | Case 2 | | |
| 7 | 21.667 | 24.000 | 15.500 | 14.833 |
| 14 | 20.333 | 21.833 | 14.833 | 13.833 |
| 28 | 18.250 | 19.500 | 13.500 | 12.500 |

Pulse velocity measurements were also taken by measuring transit time of propagation of compressional waves for all of the specimens (see Table 6). Results indicate that the control samples had the lowest average values for transit time, followed by the lab-tested specimens, the Case 1 C&D and the Case 2 C&D respectively. These results show a good correlation with the Schmidt hammer test results, as well as the results of the other strength tests.

Table 6: Transit time( μs) and Pulse Velocity(m/s) of three specimens for each aggregate source

| Curing time (Days) | C&D concrete waste | | | | Lab-tested concrete waste | | Control sample | |
|---|---|---|---|---|---|---|---|---|
| | Case 1 Transit Time(μs) | Pulse velocity (m/s) | Case 2 Transit Time(μs) | Pulse velocity (m/s) | Transit Time(μs) | Pulse velocity (m/s) | Transit Time(μs) | Pulse velocity (m/s) |
| 7 | 50.20 | 5977.67 | 72.77 | 4124.67 | 48.23 | 6220.00 | 46.27 | 6484.67 |
| 14 | 50.87 | 5899.33 | 68.83 | 4359.00 | 47.93 | 6258.67 | 46.40 | 6466.33 |
| 28 | 49.90 | 6061.67 | 66.80 | 4492.00 | 48.13 | 6233.00 | 45.90 | 6537.00 |

### *4.5 Correlation of Mechanical Properties*

Correlations between the mechanical properties of the different samples were calculated in order to determine the relevance of the results, based on the Pearson correlations calculations; in particular, the correlations between the results of the compressive strength tests and the results of the other tests, including the NDT tests, were calculated for C&D case1.

The correlation between compressive strength and split tensile strength is shown in Figure 3 and by Eq. (1). A linear relationship is also noted between these two properties ($R^2$= 0.9798).

$$S_t = 1.1431\, f'c - 36.712 \qquad (1)$$

Where $S_t$ is the split tensile strength in MPa and $f'c$ is the compressive strength in MPa.

The correlation between compressive strength and flexural strength is shown in Fig. 4 and by Eq. (2). A linear relationship could also be noted between these two properties. ($R^2$= 0.997)

$$fr = 4.163\, f'c - 139.31 \qquad (2)$$

Where *fr* is the flexural strength (MPa) and *f'c* is the compressive strength (MPa).

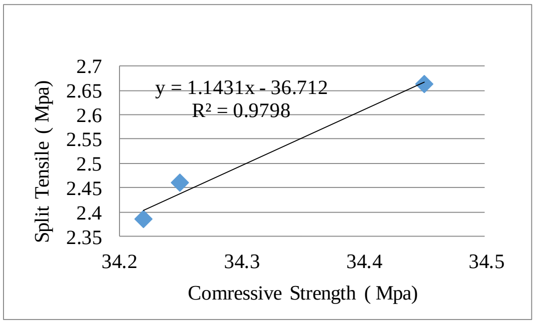


Figure 3: Correlation between compressive strength and split tensile strength of specimens after 28 days

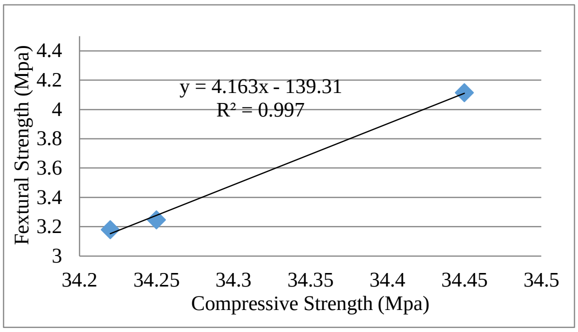


Figure 4: Correlation between compressive strength and flexural strength of specimens after 28 days

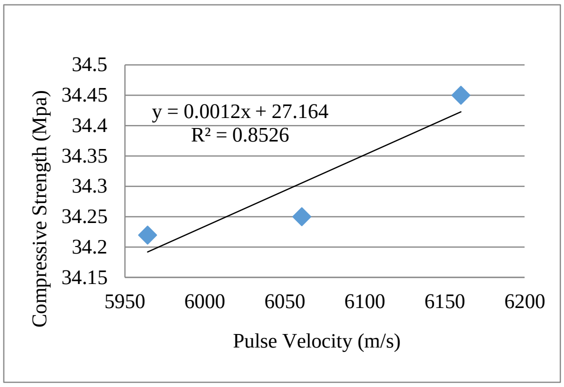


Figure 5: Correlation between compressive strength and pulse velocity of specimens after 28 days

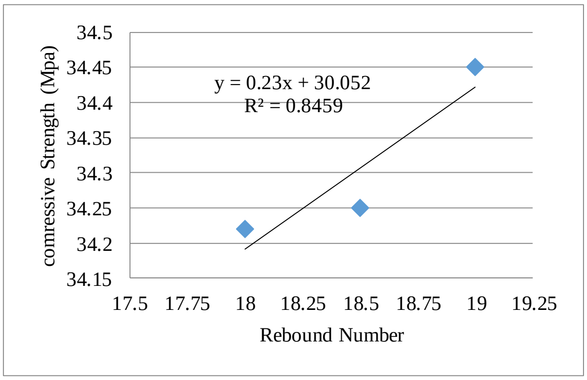


Figure 6 : Correlation between compressive strength and Schmidt hammer of specimens after 28 days

The relationship between compressive strength and pulse velocity is shown in Fig. 5 and by Eq. (3). Almost a linear relationship ($R^2$= 0.8526) could be noted between these two properties.

$f'c = 0.0012\,PV + 27.164$……………………..…………………………………………………………...(3)

Where *PV* is the pulse velocity in m/s and *f'c* is the compressive strength in MPa.

The relationship between compressive strength and rebound number in Schmidt hammer tests is shown in Fig. 6 and by Eq. (4). Almost a linear relationship ($R^2$=0.8459) could be noted between these two properties.

$f'c = 0.23RN + 30.052$……………………………………………..……………………………………………(4)

Where *RN* is the rebound number and *f'c* is the compressive strength in MPa.

## 5. Conclusion

An experimental program was designed to compare the engineering properties of aggregate from various sources: lab-tested concrete waste from a commercial ready-mix company with known engineering properties, reclaimed construction and demolition (C&D) concrete waste with a little information from two different sites (case study 1 and case study 2), and regular aggregate from the market. Mechanical properties for case 1 (mosque) were compared with that of the control samples. The bulk density (unit weight) of the C&D waste for case 1 was higher than the market product, whereas the number of voids was less. The specific gravity increased as the absorption decreased. The specific gravity of crushed recycled aggregate was lower than that of the otherwise identical virgin aggregate, which usually has values of about 2.2 to 2.5 in the saturated surface-dry (SSD) condition. The absorption value for the recycled aggregate was much higher than that of the similar virgin aggregate, most likely due to the cement mortar attached to the particles. For compressive strength, it was found that the control sample had the highest strength, with an average value of 41.6 MPa. The results also show that the average compressive strength of C&D concrete waste for case 1had the highest value of 34.3 MPa, which is nearest to the designed compressive strength of 35 MPa. It was noted for the C&D concrete waste that the increase in compressive strength of the concrete lead to an increase in flexural strength and split tensile strength, with high correlation values ($R^2$= 0.9798 and $R^2$= 0.997) for split tensile and flexural strength, respectively, while the correlation value between compressive strength and NDT was lower ($R^2$= 0.8526 and $R^2$=0.8459) for pulse velocity and Schmidt hammer, respectively.

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