Use of Waste Ferrochrome Slag as a Sustainable Building Material for Extreme Environments

K M A Sohel, K Al-Jabri, M Z Islam and A A R Al-Shereiqi

Civil and Architectural Engineering Department, Sultan Qaboos University, P.O. Box 33, Al-Khoudh 123, Oman
kmasohel@squ.edu.om

Abstract. Ferrochrome slag is an industrial by-product material extracted during the production process of ferrochrome alloy, which is mostly used in the stainless steel industry. Large quantities of ferrochrome slag are generated annually from the steel companies in the Sultanate of Oman. The vast majority of the quantities are not used in any application and are disposed of without being reused, posing a threat to the local environment. There has been an increasing emphasis in recent years on the use of different waste materials as construction materials, which may help to alleviate environmental and ecological challenges. The physical, mechanical, chemical and thermal properties of ferrochrome slag (FCS) are favorable to be used in concrete for extreme environments such as high temperature and corrosive environments. In this study, the effect of using ferrochrome slag as a substitute for natural fine and coarse aggregates (incremental range from 25% to 100%) on the strength of concrete at elevated temperatures (ranging from 200°C to 1000°C) was investigated. Acid resistance of FCS concrete was also investigated. It is found that the inclusion of FCS enhances the compressive strength of the concrete. The thermal properties of FCS aggregate positively affect the fire resistance of the FCS concrete. The FCS concrete shows better performance in an aggressive environment than conventional concrete. Therefore, waste ferrochrome slag may be an alternative option to be used as green coarse and fine aggregates in the production of concrete.

1. Introduction
Concrete is the world’s most common and widely utilized construction material. Due to the faster construction development in recent decades, meeting the global demand for concrete is now becoming more challenging as the earth’s resources are limited. Despite this, more than three-quarters of new mixed concrete is still composed of natural aggregates. According to some research estimates [1], the annual consumption of sand, gravel, and crushed rock in the world was in the order of 28 gigatonnes in 2017. As a result of environmental, economic, and technological issues, more emphasis is being placed on the use of recycled materials and industrial waste by-products in concrete.

In recent years, research efforts have been given on the usage of solid waste and industrial by-product materials as construction materials in civil structures; this may partially help to solve the environmental and ecological challenges [2,3]. Intensive research investigations have been done to discover all potential reuse techniques of industrial waste materials in response to increased environmental pressures to minimize waste and pollution [4–6]. The use of these wastes not only allows them to be used in cement, concrete and other building materials but also reduces the cost of producing cement and concrete. It also has a number of secondary benefits, including reduced disposal and landfill costs, energy savings, and the protection of the environment from potential contamination. Moreover, the utilization of these waste products may enhance the micro-structural, strength, and durability properties.
of the concrete, which may not be achievable with conventional materials [5]. Some industrial waste and by-product materials have demonstrated their potential to be used in the production of concrete, while others are currently being researched for prospective applications. Another effort has recently been made to use recycled aggregate in the production of fresh concrete [7]. Rather than using recycled aggregates in concrete, some of the industrial waste materials and by-products have been widely used in infrastructure projects. For example, steel slag, a by-product material from the steel production process, was used as a coarse aggregate in concrete for road construction for many years [8–11]. There are many types of solid waste and by-products materials, namely: spent catalyst, steel slag, waste glass, waste plastic, scrap tyres, coal fly ash, cenospheres, rice husk ash, wood ash, etc., which have been extensively researched in different countries around the world [4,6]. Ferrochrome slag (FCS), like other waste materials, is a potential industrial by-product material that may be utilized as both coarse and fine aggregates in the production of concrete. It is produced as a by-product during the production of ferrochromium alloy, an important element of stainless steel. The majority of FCS is produced in South Africa. The estimated global production of FCS was approximately 11.7 million tonnes in 2017 [12]. While, Oman produces approximately 0.355 tons of ferrochrome slag (FCS) per year, the majority of which is disposed of as a landfill, posing a threat to the local environment [2,13]. The FCS is produced at a temperature range of 1550 to 1750°C in a liquid form. After cooling, the FCS solidifies into a rock-like solid and turns grey in color [3]. Different studies showed that the physical, mechanical and chemical properties of FCS are suitable for use as an aggregate in concrete production [2,3]. FCS has a stable chemical composition and is not soluble under normal environmental conditions [3]. It has been shown in different studies that the leaching of harmful substances from FCS aggregate concrete is very low and their concentration was within the permissible limit set by EPA [3,9,14].

As FCS contains some metallic compounds and is produced at high temperatures, it has superior thermal properties to conventional aggregate [2]. Therefore, the use of ferrochrome slag as both fine and coarse aggregates in a concrete mixture may improve thermal and mechanical properties by reducing temperature gradients and increasing temperature stability. There has been very little effort made around the world to use ferrochrome slag as both fine and coarse aggregates in concrete, as well as to investigate its behaviour at high temperatures and in aggressive environments. Therefore, the purpose of this study is to investigate the effect of FCS as fine and coarse aggregates on the physical and strength properties of the concrete at elevated temperatures and in an acidic environment.

2. Use of ferrochrome slag as a sustainable construction material

Aggregates (coarse and fine) are the most important components of concrete, accounting for roughly 70% of the total volume. Currently, about 3.7 billion tons of natural aggregate are produced globally for the construction industry [15]. Accordingly, the demand for concrete will increase steadily in the coming years, which will increase the pressure on the environment and natural resources and increase the tendency to look for alternatives that are more environmentally friendly. According to the review report by Fares et al. [3], ferrochrome is one of the possible alternative aggregates that can be used effectively in the production of concrete. Powder form of ferrochrome slag with an activator can also be used as a cementitious material, which can partially replace the Portland cement. Besides the concrete production and cement manufacturing, because of its exceptional combination of high strength and refractory properties, FCS can be used in many other applications, including subgrade of road construction, refractory materials and land filling material [3,16]. FCS may be created in granular size (0.01 to 5 mm) using a water cooling system, while FCS can be made in large size (10 to 40 mm) using an air cooling system. Large chunks of FCS may be crushed into various sizes for use in concrete production [9]. In general, FCS as an aggregate in concrete enhances the mechanical properties of concrete compared to the natural aggregate concrete [2,3]. The potential alkali-aggregate reactivity test showed that the reaction between alkali hydroxide of hydrated cement and FCS aggregate was very minimum and the expansion of FCS mortar specimen was much less than the permissible limit of 0.1% expansion [17]. Therefore, FCS, like natural aggregate, can be used in concrete as an inert aggregate. Since FCS has good adhesion, good wears resistance, superior spalling and thermal shock resistance, and higher
angularity than the normal aggregate [8,16]. However, a huge amount of FCS is still disposed of in stockpiles or dumps without further reuse [13]. FCS has better thermal properties than natural aggregates, such as high melting temperature (>1500°C) and higher thermal conductivity. Therefore, this slag aggregate can be a good alternative to natural siliceous or calcareous aggregates for high-temperature applications. The stable chemical composition of FCS may be favourable to use in an aggressive environment [3].

3. Experimental investigation

Locally manufactured ordinary Portland cement, natural aggregates (NA) and ferrochrome slag were used to produce the concrete mix for the test samples. The coarse aggregates ranged in size from 10 mm to 20 mm. Crushed stone sand and granulated ferrochrome slags were used as fine aggregates. Both coarse and fine slag aggregates samples were collected from the stainless steel production industry in Suhar, Oman. The shape and color of FCS aggregates are shown in Figure 1. The physical properties of FCS and natural crushed stone aggregates are shown in Table 1. The major chemical composition of FCS aggregates used in this study consists of Silica (SiO$_3$), Magnesia (MgO) and Alumina (Al$_2$O$_3$) [2].

![Figure 1. (a) Coarse FCS aggregate and (b) Fine FCS aggregate](image)

| Parameters                        | Type of aggregate |
|-----------------------------------|-------------------|
|                                   | FCS              | Natural         |
| Specific gravity                  | 2.85             | 2.75            |
| Water absorption (%)              | 1.41             | 0.90            |
| Loose Bulk density (kg/m$^3$)     | 1586.14          | 1562.81         |
| Aggregate crushing value (%)      | 20.45            | 19.0            |

3.1. Concrete mix design

Two groups of concrete mixes were designed in this experimental study. One group was designed to produce C40 grade concrete for only fine aggregate replacement with granulated FCS slag. The mix proportion for the control mix of this group was 1:1.5:2.6 (cement: sand: aggregate), and the water to cement ratio of 0.45 was set after a few trials. In the first group, four additional concrete mixes comprising 25%, 50%, 75%, and 100% ferrochrome slag in place of natural fine aggregate were utilized, as shown in Table 2. The second mixture group was designed for both coarse and fine aggregates replacement with FCS aggregates. For the second group, the proportion of the mix design was
1:1.74:2.41 (cement: sand: aggregate), and the water to cement ratio of 0.49 was set to produce C35 concrete. Table 3 shows the mix proportions of five mixes from the second group.

Table 2. Mix design of concrete with FCS fine aggregate for 1 m³

| Mixes | Water-cement ratio | Cement (kg) | Natural coarse aggregate (kg) | Natural fine aggregate (kg) | FCS fine aggregate (kg) |
|-------|-------------------|-------------|-------------------------------|---------------------------|------------------------|
| Control | 0.45              | 447.0       | 1182.30                       | 656.80                    | --                     |
| 25%FCS |                   | 447.0       | 1182.30                       | 492.60                    | 164.20                 |
| 50%FCS | 0.45              | 447.0       | 1182.30                       | 328.40                    | 328.40                 |
| 75%FCS |                   | 447.0       | 1182.30                       | 164.20                    | 492.60                 |
| 100%FCS |                 | 447.0       | 1182.30                       | --                        | 656.80                 |

Table 3. Mix design of concrete with FCS as both fine and coarse aggregates for 1 m³

| Mixes | Water-cement ratio | Cement (kg) | Coarse aggregate (kg) | Fine aggregate (kg) |
|-------|-------------------|-------------|-----------------------|---------------------|
|       |                   |             | Natural              | FCS                 |
|       |                   |             | Natural              | FCS                 |
| Control |                 | 442.0       | 1067.0               | -                   | 711.0                 | -                     |
| 25%FCS |                 | 442.0       | 800.0                | 267.0               | 533.0                 | 178.0                 |
| 50%FCS | 0.49             | 442.0       | 533.0                | 533.0               | 356.0                 | 356.0                 |
| 75%FCS |                 | 442.0       | 267.0                | 800.0               | 178.0                 | 533.0                 |
| 100%FCS |                | 442.0       | -                    | 1067.0              | -                     | 711.0                 |

Cubes (150 mm) and cylinders (ϕ150 × 300 mm²) specimens were cast to determine different mechanical and physical properties of the concrete at normal and extreme environments. Concrete mixing and sample preparation were performed in accordance with ASTM C192/C192M [18], as shown in Figure 2. After casting, all the specimens were demoulded after 24 hours and their details were marked on the upper surface for identification. The demoulded samples were immersed in a water chamber for curing. The samples were removed from the water before one day of testing to reduce surface moisture and spalling of the concrete when exposed to heat.

The effect of high temperature on concrete specimens was investigated using the test procedure described in reference [2]. For each composition, three samples were tested to evaluate the characteristics strength of the concrete at elevated temperatures ranging from 200 to 1000°C. A slow heating rate of 6-7°C/min was adopted as the initial heating rate of the oven. The idealized heating regimes inside the electric oven are shown in Figure 3. The heating rate after 400°C slowed down to 2°C/min automatically. The installed thermocouples (K-type) were used to record temperatures at the core of cylinder and prism samples. The acid resistance of the concrete cylinders was assessed by mass loss and residual compressive strength after immersion of the cylinders in 5% sulfuric acid solution for three months following the test procedure described in reference [19].

Figure 2. Concrete production with FCS, (a) dry mix, (b) pouring of moulds on a vibration table, and (c) samples marked on top surface and submerged in the tank for curing.
4. Results and discussion

4.1. Physical properties of concrete with ferrochrome slag (FCS) aggregates

The workability of concrete mixtures containing FCS as a fine aggregate replacement is shown in Figure 4(a). While Figure 4(b) shows the workability of concrete containing ferrochrome slag in lieu of both fine and coarse aggregates. As can be seen, the workability of concrete mixes containing ferrochrome slag aggregate decreases as the slag aggregate content increases in both cases. This is due to the fact that slag aggregates have a rougher surface structure and more pores than natural aggregates, allowing them to absorb more water. Superplasticizer was added during the concrete mixing process to improve the workability of FCS concrete.

4.2. Compressive strength

The influence of FCS aggregates on the compressive strength of concrete was assessed by testing standard cubes at the age of 28 days. The test results are presented in Figure 5. The cube compressive strength of the concrete was continuously increased as the content of FCS fine aggregate increased up to 75%, as shown in Figure 5(a). At 75% and 100% replacement, the strength remained almost constant. On the other hand, in the case of both fine and coarse aggregate replacement with FCS aggregates, the compressive strength was continually increased up to 50% replacement, as can be seen in Figure 5(b). There is a slight reduction in compressive strength on 75% and 100% replacement compared to the strength at 50% replacement. However, with these two replacements, the compressive strength of the FSC concrete was still about 14% more than the concrete with natural aggregates. The higher bond strength of FCS aggregates to cement paste than natural aggregates to cement paste contributes to the increased strength of FCS concrete. FCS aggregates have a higher surface roughness than natural aggregates, which contributes to the improved bond strength in FCS concrete. FCS aggregates absorb more water than natural aggregates because of their rough surface and porous nature. Therefore, the effective water to cement ratio in FCS concrete was lower than in reference conventional concrete, resulting in an increase in the compressive strength of FCS concrete. The relatively higher crushing value of FCS aggregate compared to the natural aggregate also contributed to an increase in the compressive strength of FCS concrete. At higher levels (over 50%) of both fine and coarse FCS aggregates content, concrete suffered from compaction difficulty due to higher angularity and surface roughness of FCS aggregates, which may have resulted in a higher amount of voids in the concrete. Therefore, the compressive strength of concrete containing 75% and 100% FCS aggregates was slightly reduced.
Figure 4. Workability of concrete with (a) slag as a fine aggregate, (b) slag as both fine and coarse aggregates

Figure 5. Cube compressive strength (a) concrete with FCS fine aggregate and (b) concrete with both fine and coarse FCS aggregates

4.3. High-temperature effect on ferrochrome slag (FCS) concrete

It is generally understood that when the temperature rises, the strength properties of the heated concrete decrease. The factors affecting the strength properties at elevated temperatures are cement paste, aggregates type and heating rate. The reduction rate of residual cube compressive strength of the concrete with different percentages of FCS aggregate content at elevated temperatures is presented in Figure 6.

The general trend was that the concrete was gaining slight strength in the exposure temperature of 200°C. While the strength was sharply decreasing in the temperature range of 400 to 800°C. The residual strength after exposure to 1000°C was less than 8%, as can be seen in Figure 6.

The strength gaining at 200°C temperature was due to the accelerated reaction between released water vapour and unreacted cement particles [20]. Furthermore, the fire test was performed after 28 days of water curing. Therefore, all cement particles did not react at the concrete age of 28 to 30 days. Different researches in the literature have also shown that if the concrete age is less than 90 days, it may gain
slight strength when exposed to temperatures between 120°C and 300°C [2]. Another reason might be that when the C-H-S gel moves closer together at high temperatures, van der Waals forces of attraction rise [21]. The rate of strength loss after being exposed to temperatures above 400°C is consistent with previous similar studies published in the literature [20,22–24]. The cube compressive strength of concrete containing FCS fine aggregate decreased progressively until 600°C, then dropped rapidly between 600°C and 800°C. In general, the concrete containing FCS fine aggregate shows slightly better performance at elevated temperatures than conventional aggregate concrete. For example, the residual cube compressive strengths after exposed to 600°C temperature were 64.11%, 62.42%, and 59.24% for the mixes 25% FCS, 50% FCS, and 75% FCS, respectively. Whereas, for the control mix, the residual cube compressive strength was 59.20% after being exposed to 600°C temperature.

**Figure 6.** Relative compressive strength of concrete with different percentages of ferrochrome slag as a fine aggregate after being exposed to elevated temperature.

### 4.4. Acid resistance of ferrochrome slag (FCS) concrete

The sulfuric acid attack occurs mostly in concrete when contact with a source of sulfuric acid in industrial areas. Thus, the ability of the concrete specimens to withstand deterioration was examined after 28 days of curing in water and 12 weeks of curing in a 5% sulfuric acid solution. The performance of the concrete specimens was assessed based on the change in compressive strength and mass on the testing day. Concrete with both fine and coarse ferrochrome slag aggregate was used to evaluate the acid resistance.

Figure 7 shows the physical appearance of control and ferrochrome slag (fine and coarse) concrete specimens (cylinders) after being exposed to the sulfuric acid solution for 12 weeks (3 months). The surface of all samples was deteriorated due to acid attack and the coarse aggregates were exposed. However, the surface deterioration of specimens with 100% FCS aggregate was much less than that of other concrete samples. Figure 8(a) shows the compressive test results of control and FCS concrete specimens treated under water and acid solutions. Significant strength reduction of all mixes exposed to H₂SO₄ solution was observed compared to their corresponding mixes cured in water. However, 100% FCS concrete lost the least strength due to the acid attack for three months. The strength loss was only 1.8%. On the other hand, the control concrete experienced about 17% reduction in strength due to the acid attack for three months. It can be seen in Figure 8(a) that 25% FCS and 75% FCS concrete have significant reduction in strength compared to the control concrete. The loss of compressive strength was 29% and 27% for 25% FCS and 75% FCS concrete, respectively. Similarly, 50% FCS concrete lost 22.6% of compressive strength due to the acid attack for three months. The discrepancy in the reduction of compressive strength could be attributed to the presence of higher surface pores on the cylinder specimens and poor concrete compaction during casting. There is no evidence of the strength reduction in these mixes due to the presence of different percentages of ferrochrome slag aggregates.
Furthermore, the weight loss of control and FCS concrete is shown in Figure 8(b). Control, 50% FCS and 100% FCS concrete mixtures experienced similar percentage of weight loss, i.e. about 13.8%. However, 25% FCS and 75% FCS concrete experienced weight loss of 16.0% and 16.5% respectively due to acid attack for 3 months. The weight loss is consistent with the strength reduction as discussed above.

![Figure 7. Cylinder specimens after exposure of 5% sulfuric acid solution for 3 months](image)

![Figure 8. (a) Compressive strength and (b) weight loss concrete with FCS aggregates (fine and coarse) submerged in the sulfuric acid solution for three months.](image)

In general, as the slags replacement increased, the rate of compressive strength loss decreased except for mixes containing 25% and 75% FCS aggregates. In case of control and other concretes, the cement paste was reacted with sulfuric acid and the effective cross-section of the concrete cylinders was reduced due to the lack of cement paste which was attacked by sulfuric acid. As a result, the control and 25% FCS concrete lost a higher level of compressive strength. On the other hand, the high alkalinity of the FCS aggregates was contributed to reduce the acid strength in the solution, and as a result, 100% FCS aggregate concrete gives higher resistance against acid attack.
Overall, the concrete exposure to sulfuric acid mostly affected on the concrete surface. If it has a low porosity which limits the ingress of acid solution and other harmful material into the concrete specimens. The acid attack occurs according to the following reaction:

\[ \text{H}_2\text{SO}_4 + \text{Ca(OH)}_2 \rightarrow \text{CaSO}_4\cdot\text{H}_2\text{O} \]

5. Conclusions
In this experimental study, industrial waste material was used in concrete production to save natural resources. Different physical properties of ferrochrome slag aggregates are similar to those of natural aggregates used in concrete production. FCS aggregates have a negative impact on the workability of concrete. The negative effect of FCS aggregates in concrete can be mitigated by using a superplasticizer. There is a positive effect of FCS aggregates on the compressive strength of concrete. Generally, the compressive strength was increased with the increase of FCS aggregates content in the concrete. All concrete mixtures lost their strength as the heating temperature raised over 200°C. However, the concrete with FCS fine aggregate experienced slightly less reduction in compressive strength than concrete with natural aggregates. At an exposure temperature of 1000°C, all concrete mixtures lost more than 90% of their compressive strength.

All mixes exposed to H\(_2\)SO\(_4\) lost a certain percentage of their strength compared to their corresponding mixes cured in water. Better acid resistance was developed for 100% FCS concrete compared to the control concrete. All mixes lost an amount of weight due to acid attacks. However, 100% FCS concrete lost less weight than control concrete.

The findings of the study show a promising potential for using waste FCS solids as a partial or full replacement of natural aggregates in the production of concrete, resulting in an environmental-friendly and sustainable concrete for normal and extreme environments. In this regard, it can be assumed that locally produced ferrochrome slag may open a new path for an economic and pollution-free concrete industry if desired strengths and durability performances can be optimized and achieved.

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References
[1] OECD 2019 Global Material Resources Outlook to 2060 (Paris: OECD)
[2] Islam M Z, Sohel K M A, Al-Jabri K and Al Harthy A 2021 Properties of concrete with ferrochrome slag as a fine aggregate at elevated temperatures Case Stud. Constr. Mater. 15 e00599
[3] Fares A I, Sohel K M A, Al-Jabri K and Al-Mamun A 2021 Characteristics of ferrochrome slag aggregate and its uses as a green material in concrete – A review Constr. Build. Mater. 294 123552
[4] Al-Jabri K, Al-Kamyani Z, Al-Shamsi K, Al-Saidy A and Sohel K M A 2021 Spent fluid cracking and spent alumina catalysts as sustainable construction materials in concrete Innov. Infrastruct. Solut. 6 3
[5] Siddique R 2008 Waste materials and by-products in concrete (Springer Berlin Heidelberg)
[6] Sohel K M A, Liew J Y R and Fares A I 2021 Shear bond behavior of composite slabs with ultra-lightweight cementitious composite J. Build. Eng. 44 103284
[7] Xiao J, Li W, Fan Y and Huang X 2012 An overview of study on recycled aggregate concrete in China (1996–2011) Constr. Build. Mater. 31 364–83
[8] Lind B B, Fällman A M and Larsson L B 2001 Environmental impact of ferrochrome slag in road construction Waste Manag. 21 255–64
[9] Panda C R, Mishra K K, Panda K C, Nayak B D and Nayak B B 2013 Environmental and technical assessment of ferrochrome slag as concrete aggregate material Constr. Build. Mater. 49 262–71
[10] Maghool F, Arulrajah A, Du Y J, Horpibulsuk S and Chinkulkijniwat A 2017 Environmental impacts of utilizing waste steel slag aggregates as recycled road construction materials *Clean Technol. Environ. Policy* 19 949–58

[11] Qasrawi H, Shalabi F and Asi I 2009 Use of low CaO unprocessed steel slag in concrete as fine aggregate *Constr. Build. Mater.* 23 1118–25

[12] Pariser H H, Backeberg N R, Masson O C M and Bedder J C M 2018 Changing nickel and chromium stainless steel markets - a review *J. South. African Inst. Min. Metall.* 118 563–8

[13] Al-Jabri K S 2018 Research on the use of Ferro-Chrome slag in civil engineering applications *MATEC Web Conf.* 149 01017

[14] Dash M K and Patro S K 2021 Performance assessment of ferrochrome slag as partial replacement of fine aggregate in concrete *Eur. J. Environ. Civ. Eng.* 25 635–54

[15] Prem P R, Verma M and Ambily P S 2018 Sustainable cleaner production of concrete with high volume copper slag *J. Clean. Prod.* 193 43–58

[16] Kumar P H, Srivastava A, Kumar V and Singh V K 2014 Implementation of industrial waste ferrochrome slag in conventional and low cement castables: Effect of calcined alumina *J. Asian Ceram. Soc.* 2

[17] Ojha P N, Singh A, Singh B and Patel V 2021 Experimental investigation on use of ferrochrome slag as an alternative to natural aggregates in concrete structures *Res. Eng. Struct. Mater.*

[18] ASTM C192/C192M 2016 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory *Am. Soc. Test. Mater.* 1–8

[19] Matalkah F, Salem T and Soroushian P 2018 Acid resistance and corrosion protection potential of concrete prepared with alkali aluminosilicate cement *J. Build. Eng.* 20 705–11

[20] Hager I 2013 Behaviour of cement concrete at high temperature *Bull. Polish Acad. Sci. Tech. Sci.* 61 145–54

[21] Naus D J 2006 *The Effect of Elevated Temperature on Concrete Materials and Structures - a Literature Review.* (Oak Ridge, TN (United States))

[22] Arioz O 2007 Effects of elevated temperatures on properties of concrete *Fire Saf. J.* 42 516–22

[23] Shang X and Lu Z 2014 Impact of high temperature on the compressive strength of ECC *Adv. Mater. Sci. Eng.* 2014

[24] Al-Jabri K S, Waris M B and Al-Saidy A H 2016 Effect of aggregate and water to cement ratio on concrete properties at elevated temperature *Fire Mater.* 40 913–25