PUBLISHED PROJECT REPORT PPR736

Use of recycled and secondary aggregates in Qatar
Guidance document

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Prepared for: Qatar National Research Foundation,
Project Ref: NPRP 4-188-2-061

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Contents amendment record

This report has been amended and issued as follows:

<table>
<thead>
<tr>
<th>Version</th>
<th>Date</th>
<th>Description</th>
<th>Editor</th>
<th>Technical Referee</th>
</tr>
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<tbody>
<tr>
<td>1.0</td>
<td>21/03/14</td>
<td>Initial draft for comment</td>
<td>J M Reid</td>
<td>D Gershkoff</td>
</tr>
<tr>
<td>2.0</td>
<td>29/01/15</td>
<td>Final draft for approval</td>
<td>J M Reid</td>
<td>D Gershkoff</td>
</tr>
<tr>
<td>3.0</td>
<td>15/05/15</td>
<td>Final version for publication</td>
<td>J M Reid</td>
<td>D Gershkoff</td>
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</table>
Executive Summary

This document presents guidance on how to use recycled aggregates in concrete, asphalt and as unbound fill materials in building and infrastructure projects in Qatar. There has been a great increase in the rate of construction in Qatar over the last decade and the rate is set to increase further in the run up to the World Cup in 2022. The boom in construction requires a sustainable supply of aggregates. To date, most aggregates for concrete and asphalt have been imported, as Qatar has very limited reserves of aggregate. Many of the existing local sources will be exhausted in a few years at current rates of extraction. The capacity of the ports is insufficient to handle all the aggregate that will be required, even allowing for planned expansions. At the same time, vast quantities of construction, demolition and excavation waste are dumped in the desert outside Doha, causing damage to the environment. These materials, and other waste streams from industrial processes, could potentially be processed into aggregates, helping to reduce dependence on imports. This is in line with the Qatar National Vision of ensuring that economic growth is balanced with protection of the environment.

There has been limited use of recycled aggregates in the Gulf until recently; contractors have preferred to use natural aggregates that are regarded as clean and consistent in quality, even if it means importing them from a considerable distance at high cost. However, recycled aggregates are widely used in other countries. Provided adequate quality control of production is maintained, recycled aggregates are capable of use in a wide range of applications.

The various materials from which recycled aggregates can be obtained are described and the potential uses for each material are discussed. Maximising the use of recycled aggregates will require major changes to demolition practices and the way in which waste from construction and excavation is handled to ensure that contaminants are removed before the materials are sent for processing. The possible end uses are illustrated by case studies from Qatar and elsewhere in the Gulf.

Using recycled aggregates is not simply a case of applying the normal procedures with different materials. Recycled aggregates often differ from primary aggregates in properties such as density and water absorption; this means that standard mixes for concrete and asphalt may have to be adapted if recycled aggregates are used. Using recycled aggregates will often involve blending them with primary aggregates to obtain optimum performance. Mixing plants for concrete and asphalt will therefore need a sufficient number of storage bins to accommodate the different types of aggregate. The changes to current practice that will be required are set out in the document.

The most recent edition of the Qatar Construction Specifications (5th edition, 2014) has been updated to permit the use of recycled aggregates in unbound applications, concrete and concrete blocks. The details are summarised in the table below. Recycled aggregates will be subject to certification by Qatar Standards in the same way as other construction products, giving assurance about quality to clients, contractors and designers.

Site trials to assess the potential for recycled materials in buildings and roads were carried out and further trials are planned. Areas where further research is required are identified and recommendations for further work are given. This document will be updated as more results become available.
<table>
<thead>
<tr>
<th>Application</th>
<th>Source Material</th>
<th>Maximum Replacement Level</th>
</tr>
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<tbody>
<tr>
<td>Unbound subgrade and subbase</td>
<td>Excavation waste and demolition waste</td>
<td>100%</td>
</tr>
<tr>
<td>Blocks</td>
<td>All</td>
<td>100%</td>
</tr>
<tr>
<td>Non-structural concrete up to C25</td>
<td>Construction, demolition and excavation waste</td>
<td>20%</td>
</tr>
<tr>
<td>Non-structural concrete up to C40</td>
<td>Excavation waste and crushed concrete</td>
<td>50%</td>
</tr>
<tr>
<td>Structural concrete up to C30</td>
<td>Excavation waste and crushed concrete</td>
<td>20%</td>
</tr>
</tbody>
</table>

Use of recycled aggregates on a large scale can yield significant savings in cost and emissions of carbon dioxide compared to importing natural aggregates, as well as reducing the pressure on port facilities. Use in accordance with the Qatar Construction Specifications (5th edition, 2014) will ensure performance that is equal to or better than that given by primary aggregates. Therefore it is recommended that industry rises to the challenge and maximises the use of recycled aggregates in construction.
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1 Introduction

1.1 What is this document and why should I read it?

This document presents guidance on how to use recycled aggregates in concrete, asphalt and as unbound fill materials in building and infrastructure projects in Qatar. It is intended for use by government and private clients engaged in construction, designers, contractors and producers of aggregates, asphalt and concrete to enable them to maximise the use of recycled aggregates.

The document sets out the case for using recycled aggregates, describes the materials available, their properties and how they can be used, presents case studies and sets out the quality procedures required for production, including Codes of Practice for construction, demolition and excavation waste. Areas where further work is required are identified and recommendations are given for measures to ensure use of recycled aggregates is maximised.

Current practice in Qatar is to import all coarse aggregates for use in concrete and asphalt. Use of recycled aggregates is very limited at present. Moving to a scenario where recycled aggregates form a significant part of the aggregate supply will require changes to current practices by all stakeholders; it is not simply a case of applying the same procedures with different materials. The changes required are set out in this document.

1.2 Policy background

The Qatar National Vision 2030 (General Secretariat for Development and Planning, 2008) states that, “The National Vision builds on a society that promotes justice, benevolence and equality” and rests on four pillars of human, social, economic and environmental development. The aim is to ensure that economic growth is balanced with protection of the environment. Use of locally produced recycled aggregates, which would otherwise be dumped in the desert, is in line with this vision, resulting in lower costs than importing primary aggregates and mitigating the adverse impacts of waste disposal.

The high level principles of the Qatar National Vision 2030 are developed in more detail in the Qatar National Development Strategy 2011 – 2016 (General Secretariat for Development and Planning, 2011). The section on waste concentrates on household and commercial waste and includes a target to increase recycling of waste to 38% by 2016 from the 2011 level of 8%. This did not include consideration of construction, demolition and excavation waste and by-products from industrial processes. The importance of these materials as potential sources of recycled aggregates has now been recognised, and it is planned to introduce the use of recycled aggregates in government projects over the period to 2016.

The National Development Strategy affirms the importance of managing waste in line with the waste hierarchy, Figure 1-1, which places reuse and recycling above disposal. Production of recycled aggregates from suitable waste streams is thus in line with the waste hierarchy and the National Development Strategy.
1.3 This document

This guidance document is the final output from research project NPRP 4-188-2-061, Innovative use of recycled materials in construction funded by the Qatar National Research Fund at the Qatar Foundation. The document also draws on the results of several other recent and current projects on the use of primary and recycled aggregates in Qatar funded by the Qatar Primary Materials Company, Lafarge Qatar Quarry and others. The research was carried out and the document written by a team from TRL – QSTP-B, Qatar Standards and Qatar University.
2 Aggregate supply in Qatar

The construction boom in Qatar has resulted in an ever increasing demand for high quality aggregates. However, Qatar has very limited reserves of natural aggregates and has to import most of the coarse aggregate used in concrete and asphalt.

Bedrock in Qatar is predominantly the Dammam Formation of Eocene Age (West, 2013), a geologically young material that is mainly weak and friable limestone and dolomite, mostly not strong enough for use as aggregate in concrete and asphalt. It also contains bands of weak shale and gypsum. The Qatar Construction Specification 4th edition (QCS, 2010) did not permit the use of local limestone in asphalt and structural concrete applications. As a result, the local limestone and excavated fill materials are used mainly for unbound applications such as sub-base and pipe bedding. The number of operational quarries in limestone in Qatar has declined in recent years. Production is currently estimated at 15 - 20 million tonnes per year.

The fine aggregate in concrete is currently sourced from reserves of ancient river sand in the south west of the peninsula. This sand has to be washed to remove gravel, silt, clay and gypsum, which are deleterious to concrete. Production of washed sand is shown on Figure 2-1. However, reserves of suitable sand are limited and increasingly fine aggregate also has to be imported. Current reserves of usable quality sand in Qatar are estimated to be about 73 Mt (million tonnes). The remaining sands are either inaccessible or contaminated with high levels of gypsum. Use of dune sand is not permitted in concrete and asphalt for heritage reasons and because the grading is not suitable. The current usage of river sand for concrete manufacture is approximately 12 Mt per year. This is expected to increase by 50% to 18 Mt per year over the next 5 years (Qatar Primary Materials Company, 2013). If other sources of fine aggregate are not found, it is estimated that the reserves will be exhausted by the end of 2016.

Figure 2-1 Stockpiles of washed sand

Imported crushed rock aggregate is mainly obtained from the United Arab Emirates (UAE) and is predominantly gabbro, Figure 2-2. Approximately 1 Mt per year of high quality limestone aggregate has also been imported in the last few years. At present the
Recycled aggregates in Qatar

Imports are predominantly coarse aggregate, but because of the limited reserves of suitable sand in Qatar, it is likely that significant imports of fine aggregate will also be required in future years.

![Figure 2-2 Imported crushed gabbro](image)

Figure 2-2 Imported crushed gabbro

Figure 4 illustrates the different aggregate sizes of the imported gabbro in 2013. Approximately 82% of the imported gabbro is coarse aggregate of greater than 5.0mm in size, which are mainly used for asphalt and concrete applications. Aggregate sizes of greater than 20.0mm are generally used in the lower asphalt layers in road construction.

![Figure 2-3 Imported gabbro in 2013](image)

Figure 2-3 Imported gabbro in 2013

It is estimated that total imports of coarse and fine aggregate in 2012 to 2014 were 20 Mt/y and the demand is expected to be much higher over the next few years (Figure 2-4). Aggregates are mainly imported through the port at Masaieed, south of Doha, with smaller quantities through Lusail, Ruwais and Ras Lafan ports. The current figure of 20 Mt per year is very close to the port capacity of Masaieed and this could be a major barrier for the proposed infrastructure projects. The government plan is to increase the port capacity to about 50 Mt per year in 2015/16 (Qatar Primary Materials Company,
There is also a need to ensure quality aggregate would be continuously supplied in the quantities and timescale required.

Figure 2-4 shows the imports of gabbro aggregate between 2005 and 2014 (in blue) together with the estimated demand between 2013 and 2018 (in red). The consumption data were obtained from Qatar Primary Materials Company (QPMC, 2014). The results show a gradual increase from approximately 6 Mt in 2005 to 20 Mt in 2012. Between 2012 and 2014 the aggregate consumption was almost steady at 20 Mt/y. This steady supply of aggregate is mainly attributed to the delay in letting construction projects and concerns about the quality of imported aggregate. The quality of imported gabbro has shown considerable variation between and within sources, with the specific gravity reported as ranging from 2.7 to 3.2. This variability causes major problems with asphalt and concrete mixtures, and therefore Qatar Standards imposed a new system in 2013 for testing the aggregate on arrival at the port before it is allowed into Qatar. It is expected that a quality system is to be developed and implemented shortly to improve the quality of aggregate supply to Qatar.

![Figure 2-4 Aggregate consumption and demand in Qatar](image)

There is a great uncertainty in predicting the quantities of future aggregate demand in Qatar, mainly due to the lack of accurate information on number of project awarded; start and completion dates, and annual aggregate demand. In November 2013, the Peninsula (2013) published figures from surveys conducted by the Ministry of Development Planning & Statistics, The Ministry of Economy & Commerce, the 2022 Supreme Committee and the Central Planning Office that included aggregate future demand. The forecast for aggregate demand for 2015 was greater than 80 Mt, which is much greater than the amounts currently imported and considerably higher than the projected increased port capacity of 50 Mt per year. A more recent study on the aggregate supply chain strategy (QPMC, 2014) considered targeting a maximum demand of 50 Mt per year, which is more realistic and achievable within the plan of increasing port capacity to more than 50Mt by 2016.
While there is an element of uncertainty about the estimates of future aggregate demand, it is definite that demand for imported aggregates will outstrip current consumption over the next few years, potentially leading to delays to major projects. Recycled aggregates can help to meet this demand, and there are several streams of potentially suitable materials available in Qatar. These are described in Section 3.
3 Recycled and secondary materials available in Qatar

3.1 Construction, demolition and excavation waste

As part of the development programme, old buildings and structures are being demolished and replaced with new construction throughout the country, particularly in Doha (Figure 3-1). The construction, demolition and excavation waste is mainly taken to Rawdat Rashid, approximately 30 km from the centre of Doha, where it is deposited. The site extends over 8 to 10 km² and was formerly a limestone quarry. It is extremely busy with a long queue of trucks at peak hours. The daily input is estimated to be about 2,000 fully loaded trucks per day, giving annual arisings of about 12 Mt per year. The stockpile of unprocessed waste is estimated to be of the order of 60 to 80 Mt.

Under the previous site operator, each lorry load was inspected visually and assigned to one of the following two categories, which were deposited in different areas of the site:

- Construction and demolition waste (CDW), predominantly grey in colour; or
- Excavation waste (EW), predominantly white in colour.

Small quantities of the Excavation Waste were recycled as unbound aggregate by the previous site operator up to August 2012. Since September 2013 the site has been operated by a new contractor and production of recycled aggregates has restarted on a major scale.

The two materials are described in the following sections.

![Figure 3-1 Demolition waste in Doha](image)

3.1.1 Construction and demolition waste (CDW)

The construction and demolition waste (CDW) is produced from construction, renovation or demolition of existing buildings/structures including residential and non-residential buildings (Figure 3-1), roads, bridges etc. The composition typically includes concrete, asphalt, concrete blocks, steel, wood, glass, gypsum wallboard, ceramics and roofing,
rocks and excavation waste, mainly limestone (Figure 3-2 and Figure 3-3). The material is very variable in composition. The CDW contains varying amounts of foreign materials of plastics, wood, glass, metal, etc. (Figure 3-4). Currently there is no attempt to segregate the CDW waste into different categories, e.g. clean concrete and blocks or material with more wood, plasterboard and other contaminants.
3.1.2 Excavation waste (EW)

The excavation waste (EW) results from site preparation and the excavation of foundations, tunnels, and service trenches. As the majority of soil in Qatar is bedrock of limestone, the excavation waste is generally a relatively clean, white limestone with varying quantities of asphalt, wood, blocks and concrete (Figure 3-5). The limestone ranges from large lumps of relatively strong rock to completely broken down fine material. Most of the material contains a significant amount of fines.

Figure 3-5 Stockpile of unprocessed EW

The EW and clean concrete is processed into a range of graded and single size aggregates (Figure 3-6).
3.2 Steel slag

Steel slag is a secondary product of the steel making process with approximately 0.25 Mt produced annually, which represents about 10% of the steel production. The steelworks is an Electric Arc Furnace (EAF) owned by Qatar Steel and is located at Masaieed, south of Doha. The slag floats on the top of the molten steel and is poured off into special containers and allowed to air-cool prior to processing (Figure 3-7). The slag is transported, tipped, and allowed to air-cool under controlled conditions before processing. After cooling, the slag is processed by crushing and screening to different sizes (Figure 3-8). The steel slag is stockpiled on site.
The current production of steel is approximately 2.5 Mt per year and results in considerable quantities of solid by-products. To meet the growing demand for steel in the region, Qatar Steel is increasing its production capacity so arisings of the various by-products are likely to increase. Table 3-1 gives the types of solid waste and quantities of current arisings and stockpiles, as provided by Qatar Steel.

**Table 3-1 By-products from steel production**

<table>
<thead>
<tr>
<th>Solid waste/by-product</th>
<th>Arising (t/y)</th>
<th>Stockpiled (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EAF (Electric Arc Furnace)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EAF Slag</td>
<td>250,000</td>
<td>2,000,000</td>
</tr>
<tr>
<td>LF Slag</td>
<td>10,000</td>
<td>150,000</td>
</tr>
<tr>
<td>EAF dust</td>
<td>20,000</td>
<td>100,000</td>
</tr>
<tr>
<td>LCP (Lime Calcination Product)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone (&lt;30mm)</td>
<td>20,000</td>
<td>25,000</td>
</tr>
<tr>
<td>Dolomite (&lt;30mm)</td>
<td>20,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Hydrated Lime</td>
<td>7,000</td>
<td>5,000</td>
</tr>
</tbody>
</table>

EAF slag is by far the highest quantity of 250,000 tonnes per year. In addition, there are approximately 2 Mt of stockpiled slag that are not currently utilised. Ladle Furnace (LF) slag is produced in smaller quantities but contains lower contents of free magnesium and calcium making them more volumetrically stable. The EAF dust contains the lowest level of calcium and the highest content of magnesium, within the slag product.

The lime calcination products consist of limestone aggregate and dolomite aggregate (less than 30mm) and hydrated lime. The limestone and dolomite are natural materials which are not used in the plant because their particle size is smaller than required for the flux (30-60mm). Hydrated lime is produced from the burning (calcination) of
limestone into quicklime, which is converted into hydrated lime with the addition of water.

### 3.3 Incinerator bottom ash (IBA)

Incinerator bottom ash (IBA) is produced from the Energy-from-Waste plant located in the Domestic Solid Waste Management Centre (DSWMC) near Masaieed (Figure 3-9). The plant receives about 2,300 tonnes of household waste per day. This is expected to grow at 10 – 15% per year. Approximately 120 tonnes of incinerator bottom ash (IBA) is produced per day for 330 days/year, giving about 50,000 tonnes per year.

![Figure 3-9 Energy-from-Waste plant near Masaieed](image)

The waste is burned at 850°C for about 45 minutes and the bottom ash is quenched in water then transported to an outdoor area where it is weathered for about one month. This is a very dirty material with a lot of unburnt plastic. It is then processed to remove metals and unburnt material. The resulting incinerator bottom ash (IBA) is sent to a landfill on the site (Figure 3-10). The IBA contains a significant amount of glass, visible in the coarse fraction, and a lot of fines. It is much cleaner than the unprocessed IBA and could be a useful source of aggregate.

![Figure 3-10 Processed IBA](image)
3.4 Tyre rubber

Large quantities of tyre rubber stockpiles are available at Umm Alafai, Rawdat Rashid and DSWMC, Figure 3-11. The estimated quantities of stockpiled tyres exceed 11 Million tyres, and currently no further used tyres are collected at Umm Alafai or DSWMC. The current annual production of tyre rubber is approximately 1.5 Million tyres per year, varying between passenger cars and trucks. Assuming the average weight of car tyre is about 7.1kg (WRAP, 2006), the total stockpile is likely to exceed 80,000 tonnes, and the annual production is about 10,650 t/year.

![Figure 3-11 Stockpile of used tyres](image)

Stockpiles of tyre rubber are a potential fire risk and there is clearly a need to deal with this waste stream. Most tyres in Qatar are processed into shredded and crumb rubber with potential use in construction and floor industry. Unlike primary aggregates, tyre rubber is elastic and lightweight and therefore can be considered for specific applications such as bitumen modifier, aggregate in concrete or in sports and play surfaces.

3.5 Crushed rock fines (CRF)

To extend the life of the natural deposits of sand used for fine aggregate, the use of crushed rock particles of less than 5 mm size has been investigated; these materials are known as crushed rock fines (CRF). The use of crushed gabbro and limestone fines has been investigated. The fines are imported from the United Arab Emirates and so are not recycled aggregates in the same way as the other materials considered in this guidance document. However, they are included here as they are new to the construction industry in Qatar and their use is part of the process of developing a sustainable supply of aggregates for the country.

3.6 Summary of potential quantities of recycled aggregates

The estimated arisings and stockpiles of the materials described in this section are summarised in Table 3-2.
Table 3-2 Quantities of materials with the potential to produce recycled aggregates

<table>
<thead>
<tr>
<th>Material</th>
<th>Arisings (Mt/year)</th>
<th>Stockpile (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD&amp;EW</td>
<td>12.0</td>
<td>60 - 80</td>
</tr>
<tr>
<td>EAF steel slag</td>
<td>0.25</td>
<td>2.0</td>
</tr>
<tr>
<td>Incinerator bottom ash (IBA)</td>
<td>0.05</td>
<td>0.10</td>
</tr>
<tr>
<td>Tyre rubber</td>
<td>0.01</td>
<td>0.08</td>
</tr>
<tr>
<td>Total</td>
<td>12.31</td>
<td>62 2</td>
</tr>
</tbody>
</table>

It is clear from Table 3-2 that by far the most significant material in terms of contributing to aggregate demand is the CD&EW. Not all of the material in each waste stream will be suitable for processing into aggregate, and the CD&EW in particular contains a lot of contaminants and weak material. However, there is also much material that could be processed into high quality recycled aggregates. The steel slag and IBA may be more suitable for use in niche applications.

The suitability of the materials for use in different applications will be discussed in Section 4 and case studies will be presented in Section 5.
4  Suitability of materials

4.1  Construction in hot desert climates

Qatar and other GCC countries have a hot desert climate, with very low, unpredictable rainfall and very high temperatures in summer. This presents a challenging environment for construction, with a number of adverse features (Walker, 2012):

- Very high temperatures for a large part of the year making construction operations difficult and affecting curing of concrete and stability of asphalt;
- Occasional and unpredictable rainfall, often occurring as heavy storms with the potential to cause erosion and flooding, exacerbated by the lack of vegetation;
- High salt content in the soil, groundwater and many potential construction materials, with the potential to cause corrosion or expansive reactions;
- High salt content in dust in coastal areas, causing attack on exposed concrete and asphalt;
- Wind-blown sand causes abrasion to building materials and can drift over transport infrastructure during storms. The lack of vegetation means that this is a year-round problem and also causes difficulties for construction operations.

The strategy applied to counter these adverse conditions has been to use only sound rock or crushed natural gravel for coarse aggregate. The aggregates should be clean, strong, and free of salts, clay and organic matter. Water used for mixing and curing concrete should also be essentially salt-free (Walker, 2012). Using only high quality primary aggregate will minimise problems with durability. However, there is a limited supply of suitably inert aggregates (not to mention water) in desert regions, particularly low-lying states such as Qatar. It is therefore prudent to explore the use of locally available recycled aggregates, but this has to be done with knowledge of the challenges that face the materials and the issues that need to be addressed.

This chapter discusses the suitability of the recycled aggregates described in Section 3 for use in a range of applications and highlights the issues that have to be addressed in order to maximise the potential of each material.

4.2  Material suitability

None of the materials described in Section 3 are suitable for use as aggregates without processing to remove contaminants and to meet the requirements of the specification. The processing required will generally include crushing and passing through screens of different sizes to produce the correct range of particle sizes for the relevant application. Removal of contaminants can include use of magnets for ferrous metals and air blowing, washing or hand picking to remove lightweight contaminants such as wood, paper, plastic and organic matter. Weathering of slags and ashes is required to allow them to adjust to atmospheric conditions and ensure that they are volumetrically stable before use in construction.

All aggregates – recycled or primary – should be tested regularly to ensure they comply with the requirements of the specification. The quality control systems that are required are described in Section 6. In Qatar the relevant specification will usually be the latest
Recycled aggregates in Qatar

version of the Qatar Construction Specification (QCS, 5th edition 2014). In the QCS recycled aggregates are permitted in some applications but not in others, and there are limits on the proportion of different types of aggregate in some applications. The Qatar Construction Specification, and the way it has changed in recent years to enable greater use of recycled aggregates, is described in Section 7.

Aggregates other than those obtained by processing natural rock or sand and gravel deposits are sometimes subdivided into recycled and secondary aggregates. The definitions of these terms are given below (BS EN 13242:2007):

- Recycled aggregates: aggregate resulting from the processing of inorganic or mineral matter previously used in construction;
- Secondary aggregates: aggregate resulting from an industrial process involving thermal or other modification.

Thus, of the materials available in Qatar, aggregates derived from the processing of construction, demolition and excavation waste would be classed as recycled aggregates, and aggregates derived from the processing of incinerator bottom ash or steel slag would be classed as secondary aggregates. In this document all these materials are referred to as “recycled aggregates” for simplicity. Washed sand and crushed rock fines are primary aggregates, derived from the processing of natural deposits.

What matters, however, is not the origin of the aggregates but their performance. A guide to the potential suitability of the different primary and recycled aggregates available in Qatar is given in matrix form in Table 4-1 and Table 4-2. The matrices are for guidance only; in all cases users should check that the materials they propose to use conform to the requirements of the specification. The matrices are based on experience with the various materials in Qatar and elsewhere, visual observation of the materials, laboratory test results and site trials. The matrices only consider the technical aspects of the materials and will be updated as more information becomes available.

Detailed notes on the likely properties and issues of concern for the various materials are given in the following sections.
## Recycled aggregates in Qatar

### Table 4-1 Material suitability for unbound applications

<table>
<thead>
<tr>
<th>Material</th>
<th>Pipe bedding/drainage</th>
<th>General fill</th>
<th>Backfill to structures – coarse/all-in</th>
<th>Unbound subbase / all-in</th>
<th>Cement bound material</th>
<th>Railway ballast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imported gabbro (coarse)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Imported limestone (coarse)</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Crushed gabbro fines</td>
<td>√</td>
<td>×</td>
<td>X</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Crushed limestone fines</td>
<td>√</td>
<td>×</td>
<td>X</td>
<td>×</td>
<td>×</td>
<td>X</td>
</tr>
<tr>
<td>Local limestone in Qatar</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Local washed sand in Qatar</td>
<td>√</td>
<td>X</td>
<td>X</td>
<td>√</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Excavation waste (EW)</td>
<td>√</td>
<td>√</td>
<td>X</td>
<td>√</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>Construction/demolition waste (CDW)</td>
<td>√</td>
<td>√</td>
<td>X</td>
<td>√</td>
<td>×</td>
<td>X</td>
</tr>
<tr>
<td>Blends of EW and dune sand</td>
<td>√</td>
<td>√</td>
<td>X</td>
<td>√</td>
<td>×</td>
<td>X</td>
</tr>
<tr>
<td>Incinerator bottom ash (IBA)</td>
<td>X</td>
<td>√</td>
<td>X</td>
<td>√</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Electric Arc Furnace (EAF) steel slag</td>
<td>√</td>
<td>√</td>
<td>?</td>
<td>√</td>
<td>?</td>
<td>√</td>
</tr>
</tbody>
</table>

**Key**

- **Primary aggregates**
- **Recycled aggregates**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>√</td>
<td>Will generally be suitable for the application if it complies with the specification</td>
</tr>
<tr>
<td>X</td>
<td>Will generally not be suitable for the application</td>
</tr>
<tr>
<td>?</td>
<td>Uncertain; further work required to establish properties and behaviour of material</td>
</tr>
</tbody>
</table>

Recycled aggregates can be used to replace up to 100% of primary aggregates in all applications where they are shown as suitable.
### Table 4-2 Material suitability for concrete and pavement applications

<table>
<thead>
<tr>
<th>Material</th>
<th>Structural concrete</th>
<th>Non-structural concrete</th>
<th>Concrete blocks</th>
<th>Pavement Quality Concrete</th>
<th>Asphalt base/binder course</th>
<th>Asphalt wearing course</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imported gabbro (coarse)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Imported limestone (coarse)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Crushed gabbro fines</td>
<td>✓ 50%</td>
<td>✓</td>
<td>✓</td>
<td>✓ 50%</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Crushed limestone fines</td>
<td>✓ 60%</td>
<td>✓</td>
<td>✓</td>
<td>✓ 60%</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Local limestone</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>?</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Local washed sand</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Excavation waste (EW)</td>
<td>✓ 20%</td>
<td>✓ 50%</td>
<td>✓</td>
<td>✓ 50%</td>
<td>?</td>
<td>X</td>
</tr>
<tr>
<td>Construction/demolition waste (CDW)</td>
<td>✓ 20%</td>
<td>✓ 50%</td>
<td>✓</td>
<td>✓ 50%</td>
<td>?</td>
<td>X</td>
</tr>
<tr>
<td>Incinerator bottom ash (IBA)</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Tyre rubber</td>
<td>X</td>
<td>X</td>
<td>?</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Key**

- **Primary aggregates**
- **Recycled aggregates**
- ✓ Will generally be suitable for the application if it complies with the specification
- X Will generally not be suitable for the application
- ? Uncertain; further work required to establish properties and behaviour of material
- 50% Maximum level of replacement of primary aggregate by recycled aggregate or crushed rock fines
4.3 Properties of materials

4.3.1 Construction and demolition waste (CDW) and excavation waste (EW)

4.3.1.1 Quick guide

- Variable composition and degree of contamination, especially CDW;
- Generally suitable for coarse/all-in unbound applications such as subbase but may need to blend materials and/or add sand to meet the specification requirements;
- Susceptible to loss of strength if exposed to water; do not use below the water table or in areas exposed to flooding;
- Not suitable as fine aggregate because of high sulphates, chlorides, lightweight materials and fines content;
- Not suitable as backfill to structures (concrete or metal) because of high sulphate and chloride content;
- May be suitable as coarse aggregate in cement bound material but concerns about sulphate and chloride content – further work required;
- Crushed clean concrete and fresh limestone excavation waste suitable as coarse aggregate in concrete blocks and structural concrete if blended with imported primary aggregate;
- Crushed clean concrete and fresh limestone suitable as coarse aggregate in asphalt base/binder course if blended with imported primary aggregate;
- Not suitable for use in asphalt wearing course.

4.3.1.2 Typical properties – unbound applications

Most recycled aggregates available in Qatar are derived from excavation waste, and the producers are starting to produce material from clean crushed concrete. A programme of laboratory testing was therefore carried out to assess the suitability of recycled aggregates produced from crushed concrete (CDW) and excavation waste (EW) from Rawdat Rashid for use in unbound applications, in particular unbound subbase as defined in the Qatar Construction Specification 4th edition (QCS, 2010). Tests were also carried out on the excavation waste with about 20% of dune sand added (EW + DS). Dune sand is often added to the local limestone to enable it to comply with aspects of the Qatar Construction Specification, so the EW + DS samples imitated this and acted as a control sample of material that would normally be acceptable as unbound subbase.

A summary of the relevant test data is given in Table 4-3, showing the typical ranges of the main parameters. The limiting values in the 5th edition of the Qatar Construction Specification (2014) are shown for comparison. Parameters where values are sometimes in excess of the Qatar Construction Specification limiting values are highlighted in yellow. The values shown should only be regarded as indicative; the quantities of construction, demolition and excavation waste are very large and the material is highly variable, so any testing programme can only give an indication of the properties. Potential users should always check up-to-date test results to ensure that the recycled aggregates are fit for the purpose. The issue of quality control is dealt with in Section 6.
### 4.3.1.3 Issues for unbound applications

The recycled aggregates were produced to meet the grading requirements of Class B material as defined in the 4th edition of the Qatar Construction Specification (2010). The aggregates generally complied well with the grading requirements (Figure 4-1). The particle shape, as indicated by the flakiness and elongation indices, was satisfactory. However, it is known that the local limestone has a tendency to produce elongated particles unless the production process is properly controlled, so this aspect should always be checked.

**Figure 4-1 Grading of unbound recycled aggregates**

The excavation waste, which consists predominantly of local limestone, failed the sand equivalent test even when 20% of dune sand was added. We understand that limestone from most of the quarries in Qatar also fails this test. The sand equivalent test was developed as a field test to give a rapid assessment of the harmful fines content; however, these properties are determined more accurately by the particle size distribution test and plasticity index testing of the fines.

Liquid Limit values were recorded on all the materials, with all three materials giving values higher than the Qatar Construction Specification maximum value. The results of Liquid Limit, Plastic Limit and Plasticity Index showed considerable variation between samples. This reflects variation in the clay content and mineralogy in the original limestone, which is exacerbated when limestone with different sources are mixed in excavation waste. There was also considerable variation between different testing laboratories on samples of the same material.

The concern with high values of Liquid Limit and Plasticity Index is that the clay minerals in the fines will make the material susceptible to loss of strength if exposed to water. However, all the materials gave soaked CBR values well in excess of the limiting value (Table 4.3). As a matter of good practice, recycled aggregates derived from excavation waste should not be placed below the water table or where they will be inundated after heavy rainfall. In Qatar, subbase will generally be placed in dry conditions and will be covered by impermeable concrete or asphalt layers, which will prevent ingress of rainwater. TRL Overseas Road Note 31 (TRL, 1993) recommends that for granular
Recycled aggregates in Qatar

Subbases in arid and semi-arid climates, the Liquid Limit should be less than 55% and the Plasticity Index less than 20%. All the materials tested to date meet these requirements. Provided care is taken with how and where they are used, it should therefore be possible to use these materials in unbound applications such as subbase.

Table 4-3 Properties of recycled aggregates produced from crushed concrete and excavation waste

<table>
<thead>
<tr>
<th>Property</th>
<th>QCS 2014 Subbase Limiting Values</th>
<th>Crushed Concrete</th>
<th>EW</th>
<th>EW + DS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flakiness index (%)¹</td>
<td>35% max</td>
<td>11 - 24</td>
<td>14 - 28</td>
<td>12 - 31</td>
</tr>
<tr>
<td>Elongation index (%)</td>
<td>40% max</td>
<td>19 - 30</td>
<td>23 - 40</td>
<td>26 - 32</td>
</tr>
<tr>
<td>Sand Equivalent</td>
<td>25% min</td>
<td>31 - 58</td>
<td>10 - 23</td>
<td>11 - 28</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>25% max</td>
<td>Non-plastic - 45</td>
<td>37 - 60</td>
<td>Non-plastic - 29</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>6% max</td>
<td>Non Plastic</td>
<td>2 - 25</td>
<td>Non Plastic</td>
</tr>
<tr>
<td>Los Angeles abrasion (%)</td>
<td>40% max</td>
<td>30 - 35</td>
<td>26 -32</td>
<td>24 - 32</td>
</tr>
<tr>
<td>Soundness (%) (magnesium sulphate)</td>
<td>20% max</td>
<td>2 - 5</td>
<td>14 - 19</td>
<td>7 - 16</td>
</tr>
<tr>
<td>Soaked CBR (%)</td>
<td>70 % min</td>
<td>52 - 134</td>
<td>121 - 265</td>
<td>112 - 266</td>
</tr>
<tr>
<td>Swell %</td>
<td>1% max</td>
<td>0.02 – 0.17</td>
<td>0.01 - 0.16</td>
<td>0.02 - 0.13</td>
</tr>
<tr>
<td>Maximum dry density</td>
<td>2.05 Mg/m³</td>
<td>1.98 – 2.09</td>
<td>2.18 – 2.20</td>
<td>2.19 – 2.31</td>
</tr>
<tr>
<td>Acid soluble chloride (%)</td>
<td>2.0% max</td>
<td>0.13 – 0.15</td>
<td>0.08 – 0.10</td>
<td>0.07 – 0.08</td>
</tr>
<tr>
<td>Acid soluble sulphate (%SO₄)</td>
<td>3.0% max</td>
<td>1.2 - 3.3</td>
<td>1.1 – 4.4</td>
<td>1.0 - 2.8</td>
</tr>
</tbody>
</table>

Note: Highlighted cells indicate parameters which sometimes exceed the limiting values.

The issue of the Liquid Limit, Plasticity Index and Sand Equivalent exceeding the limiting values is usually addressed by mixing processed EW with 20% of dune sand. This was successful in reducing the Plastic Limit below the limiting value, and reduces the Liquid Limit below the limiting value in most, but not all samples. It made little difference to the Sand Equivalent value, with most samples still failing this test.

The particle strength (Los Angeles), durability (Magnesium Sulphate Soundness) and CBR/swell are satisfactory in almost all cases, particularly for the excavation waste materials. The excavation waste derived materials also satisfy the requirements for the

¹ Flakiness index and Elongation index have been replaced in the 5th edition by flat and elongated particles. The limiting values are those in the 4th edition, which was current at the time the tests were carried out.
minimum value of maximum dry density. However, the recycled aggregates derived from crushed concrete generally give values lower than the requirement. This may reflect the presence of mortar and the higher water absorption of the crushed concrete compared to natural aggregates.

With the exception of the Liquid Limit, Plasticity Index and Sand Equivalent, the testing indicated that the recycled aggregates should generally be suitable for unbound applications such as subbase. A site trial of the three materials was therefore carried out. Trial sections of each material, each 120 m in length, were placed as part of the reconstruction of the access road to Rawdat Rashed. The material was placed in two layers, with in-situ testing carried out on each layer. A trafficking trial was then carried out on the top layer before the overlying asphalt layer was placed.

All three materials performed well in the trial, giving a well-compacted surface that stood up to the trafficking trial very well. The trial is described in more detail in Section 5.2. The trial gives confidence that recycled aggregates derived from excavation waste and crushed concrete can be used successfully as unbound subbase and other applications provided the materials are at least 1 m above the water table.

The Qatar Construction Specification does not contain any limiting values for foreign constituents such as wood, plastic, paper, plasterboard and metal in recycled aggregates as unbound materials. Most specifications which permit the use of recycled materials, such as the UK Specification for Highway Works, do include limitations on such contaminants, as they are very unsightly as well as potentially affecting the performance of the aggregates. The 5th edition of the Qatar Construction Specification (2014) does include a test for foreign constituents and limiting values for their use in concrete. It is recommended that the test and limiting values are also adopted for unbound applications.

The fine aggregate (0/4mm) of all the materials was found to contain high levels of sulphate, chlorides and other contaminants and is not considered suitable for use in concrete or unbound applications.

The coarse and all/in aggregate (4/40 & 0/40) may be suitable as coarse aggregate in cement bound material and other hydraulically bound materials. However, there is limited experience with these materials in Qatar and the high sulphate levels and variability of the materials give some cause for concern if used in cement bound materials, as expansive reactions could occur. Cement bound material is being increasingly used in road construction in Qatar, however, and further work is required to assess the suitability of recycled aggregates for these applications.

4.3.1.4 Typical properties – concrete applications

A programme of laboratory testing was carried out to assess the suitability of CDW and EW from Rawdat Rashid and IBA from the Domestic Solid Waste Management Centre for use in concrete applications, both as fine (0/4) aggregate and coarse (4/20) aggregate as defined in the Qatar Construction Specification (QCS, 2010). A summary of the relevant test data for coarse aggregate is given in Table 4-4. Results for imported gabbro and limestone (LS), materials that are widely used as coarse aggregate in concrete are also shown for comparison. Values in excess of the Qatar Construction Specification limits are highlighted in yellow.
Recycled aggregates in Qatar

The CDW, EW and natural aggregate satisfy most of the geometric requirements of the 4th edition (2010) of the Qatar Construction Specifications. For the physical requirements, all recycled aggregates gave higher water absorption values than specified. The CDW and EW met the requirements for specific gravity and Los Angeles abrasion, but the IBA did not. All the aggregates satisfied the soundness requirement of 15% max after 5 cycles with the exception of EW which gave a slightly higher value of 16.5%. For the chemical requirements, all the tested aggregate gave higher chloride content than specified in the Qatar Construction Specification QCS 2010, and the CDW, EW and IBA exceeded the limit for sulphate content.

Table 4-4 Properties of recycled aggregates as coarse aggregate for concrete (from Hassan et al, 2013)

<table>
<thead>
<tr>
<th>Property</th>
<th>QCS 2010 Limiting Values</th>
<th>CDW</th>
<th>EW</th>
<th>IBA</th>
<th>Gabbro</th>
<th>LS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flakiness index (%)</td>
<td>30% max (reinforced)</td>
<td>11</td>
<td>8</td>
<td>16</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Elongation index (%)</td>
<td>35% max (reinforced)</td>
<td>13</td>
<td>14</td>
<td>19</td>
<td>17</td>
<td>15</td>
</tr>
<tr>
<td>Clay lumps and friable particles (%)</td>
<td>2% max</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Lightweight pieces (%)</td>
<td>0.5% max</td>
<td>0.1</td>
<td>0.1</td>
<td>8.8</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Shell content (%)</td>
<td>3% max</td>
<td>1.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Specific gravity (apparent)</td>
<td>2.6 min (reinforced)</td>
<td>2.68</td>
<td>2.70</td>
<td>2.49</td>
<td>2.92</td>
<td>2.70</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>2% max</td>
<td>4.5</td>
<td>2.3</td>
<td>5.2</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Los Angeles abrasion (%)</td>
<td>30% max</td>
<td>28</td>
<td>21</td>
<td>39</td>
<td>9</td>
<td>23</td>
</tr>
<tr>
<td>Soundness (%) (magnesium sulphate)</td>
<td>15% max</td>
<td>14.6</td>
<td>16.5</td>
<td>7.9</td>
<td>8.3</td>
<td>2.4</td>
</tr>
<tr>
<td>Organic content</td>
<td>Not darker than plate No 3</td>
<td>Lighter</td>
<td>Equal</td>
<td>Lighter</td>
<td>Equal</td>
<td>Equal</td>
</tr>
<tr>
<td>Acid soluble chloride (Cl)</td>
<td>0.03% max</td>
<td>0.15</td>
<td>0.11</td>
<td>0.11</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>Acid soluble sulphate (SO₃)</td>
<td>0.3% max</td>
<td>1.56</td>
<td>0.38</td>
<td>0.46</td>
<td>0.09</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Note: Highlighted cells indicate parameters which sometimes exceed the limiting values.

Laboratory tests for fine (0/4) aggregate were also carried out, with a local washed sand as a control, and the results are given in Table 4-4. Washed sand derived from ancient river deposits is the principal source of fine aggregate for concrete in Qatar (Section 2). Unlike the coarse aggregate, most of the properties of recycled fine aggregate did not satisfy the requirements of the Qatar Construction Specification QCS 2010. The fines content and water absorption of recycled aggregates are much higher than the washed sand, and considerably higher than the maximum specified values. The content of lightweight pieces in CDW and IBA was greater than 10 times the specified value. None of the fine aggregate, including washed sand, met the sand equivalent requirement of 70%. The organic impurities of CDW are higher than specified, which could affect the
setting of cement. The chloride and sulphate content of the recycled aggregates are also higher than the specified values.

The conclusions are that the CDW, EW and IBA may be suitable as coarse aggregate for concrete, but that they are unlikely to be suitable as fine aggregate.

Concrete trial mixtures were prepared using CDW, EW and IBA coarse aggregate as partial replacement for imported gabbro in structural (C40) grade concrete. Replacement was carried out at levels of 0, 20, 50 and 100% by weight of the gabbro. Imported limestone was also used as a control sample. Washed sand was used as the fine aggregate in all mixtures. The recycled aggregates were used as received and after treatment. The treatment for CDW and EW involved washing with water to remove dust and lightweight materials. For the IBA, the treatment included weathering with daily water spraying for at least 3 months.

The control mixtures of gabbro and limestone are commonly used within the construction industry in Qatar and were designed as C40 grade concrete for structural concrete applications. The proportion of the concrete mixture was made in the weight ratio of 1.0:2.0: 3.2 of cement: sand: coarse aggregate. A constant water/cement ratio of 0.44 was used for all mixtures and the superplasticizer dosage was adjusted to achieve a target slump of 200±20mm.

The 28 day compressive strength of the mixtures is shown in Figure 4-2 and the water absorption in Figure 4-3. The results are given for the control concrete mixtures and for recycled aggregate of 20%, 50%, and 100%. The designation of “W” is for the treated recycled aggregate. All the concrete mixtures achieved higher strength than 40 MPa except the 100% replacement with CDW and all the IBA mixtures. The highest compressive strength was obtained from the EW at 20% replacement level; this increased the 28-day strength from 47.4 to 55.5 MPa, an increment of 17%. Within the same EW material, increasing the content of recycled aggregate beyond 20% reduced the strength of the concrete. Washing the CDW with water improved the strength; however washing the EW reduced the strength. Weathering the IBA prior to use in concrete improved the strength. The control limestone concrete gave a slightly lower strength than the control gabbro.

The water absorption test gives an indication of the pore structure of concrete and its resistance to the penetration of harmful substances; the lower the water absorption, the greater the resistance. Figure 4-3 shows the water absorption values of the various concrete mixtures at 28 days. The CDW and EW gave at least similar or better results than the control concretes, except at 100% replacement levels and for washed materials. The IBA concrete gave the highest absorption values, which increased with higher IBA content.

Current practice in Qatar is to use washed quartz sand as fine aggregate in concrete. The washing is mainly for the removal of harmful clayey particles but generally reduces the content of fines passing 1mm. EW is a clean limestone aggregate containing limestone dust, which is beneficial for improving the particle packing and strength of concrete. Washing of EW removes the limestone dust and consequently the strength is reduced. In contrast CDW and IBA contain high volumes of foreign materials; these are removed by washing, and therefore the strength improves.
In summary, replacing the imported gabbro coarse aggregate with up to 50% of CDW and EW improved the strength and water absorption of concrete. Washing of CDW reduced the lightweight materials and dust content and improved the strength and absorption of the concrete. In contrast, EW does not contain a high level of lightweight materials and washing resulted in the removal of limestone dust which adversely affected the properties of the concrete.

The use of recycled aggregates in concrete blocks was also investigated. CDW, EW and IBA were used to replace both fine (0/5) and coarse (5/10) imported gabbro aggregate.
The target for each mixture was to have an average compressive strength of 10.4 MPa with the lowest individual block having a strength value of at least 8.3 MPa. This follows the Qatar Construction Specification Section 13 Part 4 (2010) requirements for load bearing walls.

All the concrete blocks made with recycled coarse aggregates showed a reduction in strength of around 10-20% compared to the control made with imported gabbro. However in the case of the CDW (50%) and IBA (20%) the average strength and minimum strength was over 10.4 and 8.3 MPa, respectively. These two mixtures therefore met the Qatar Construction Specification QCS 2010 standard for load bearing walls. Replacing the fines in the mixtures seemed to have little effect on the overall strength. However, as only a small amount of material was replaced, this was not expected to have a large effect.

In the light of these encouraging results, a full scale building trial using recycled aggregates in structural concrete and concrete blocks was carried out in Doha in 2013. This is described in Section 5.1.

4.3.1.5 Issues for concrete applications

If recycled aggregates are to be used for reducing the demand of imported aggregates, they will have to be of good quality suitable for use in concrete. There are large quantities of EW and CDW available in Qatar with potential use in structural concrete applications. Coarse recycled aggregates are more suitable than fine aggregate because of their lower water absorption and salt contents, which adversely affect the properties of concrete. Coarse aggregate of IBA also seems unsuitable for structural concrete because of its high contents of lightweight materials and sulphate but may be used in other concrete applications such as concrete blocks.

The current production of recycled aggregate in Rawdat Rashid involves crushing and screening clean sources of EW. By selecting good quality EW, the coarse aggregate could be easily used to substitute up to 50% of the imported gabbro in concrete. CDW is more variable in composition and can contain more foreign materials and salts than EW. Unless the CDW is washed during processing, or only clean sources such as recycled concrete aggregate (RCA) are processed, the material is more likely to be used in subbase applications, therefore largely replacing local limestone rather than imported gabbro.

Coarse aggregate of EW and CDW seems to satisfy most of the requirements of the Qatar Construction Specifications QCS 2010 for use as aggregate in concrete with the exception of water absorption and salts (sulphate and chloride) content. Recycled aggregate from clean sources are likely to contain low salt contents but unlikely to meet the QCS 2010 requirement for water absorption. It is therefore important to relax the water absorption requirement in national specifications provided satisfactory concrete strength and performance can be achieved.

A building trial, Section 5.1, using recycled aggregates in structural concrete and concrete blocks was constructed in June 2013 to demonstrate the successful applications of recycled aggregate in practice. The major technical barrier that can affect the uptake of recycled aggregate by the ready mix industry is the limited number of bins and storage facilities in the plants. Most concrete plants in Qatar are set up with two bins for
Recycled aggregates in Qatar

coarse aggregate; one for size 5-10 mm and the other for size 10-20 mm. To accommodate the use of recycled coarse aggregate, the plants will have to consider additional bins and storage facilities and associated infrastructure and adapt their standard mix designs. This may have cost and time implications for the ready mix industry to adapt their plants and make the necessary changes.

4.3.1.6 Asphalt applications

Typical properties for CDW, EW and gabbro coarse aggregate, compared to the maximum values for wearing course and base/binder course in the Qatar Construction Specification (2010) are shown in Table 4-5. Values which do not meet the requirements for base/binder course are shown in yellow shading. The CDW and EW fail most of the requirements for wearing course, but are more suitable for base and binder course. For this application, the water absorption exceeds the limiting values and the soundness is marginal, but the particle strength (LA value) and shape are satisfactory.

Table 4-5 Properties of recycled aggregate as coarse aggregate in asphalt

<table>
<thead>
<tr>
<th>Property</th>
<th>QCS 2010 Wearing Course</th>
<th>QCS 2010 Base/binder Course</th>
<th>CDW</th>
<th>EW</th>
<th>Gabbro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water absorption (%)</td>
<td>≤1.5</td>
<td>≤2.0</td>
<td>4.5</td>
<td>2.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Flakiness index (%)</td>
<td>≤25</td>
<td>≤30</td>
<td>11</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>Elongation index (%)</td>
<td>≤25</td>
<td>≤30</td>
<td>13</td>
<td>14</td>
<td>17</td>
</tr>
<tr>
<td>Los Angeles abrasion (%)</td>
<td>≤25</td>
<td>≤30</td>
<td>28</td>
<td>21</td>
<td>9</td>
</tr>
<tr>
<td>Magnesium sulphate soundness (%)</td>
<td>≤10</td>
<td>≤15</td>
<td>14.6</td>
<td>16.5</td>
<td>8.3</td>
</tr>
<tr>
<td>Aggregate Crushing Value (%)</td>
<td>≤20</td>
<td>≤25</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Note: Highlighted cells indicate parameters which sometimes exceed the limiting values.

By considering the particle density of aggregate in the asphalt mix design, the CDW and EW are likely to be suitable for use as coarse aggregate in base and binder course if blended with gabbro, but tests have not been carried out to confirm this or what levels of replacement would give satisfactory properties. This is an area where further work is required.

Previous work by TRL in Qatar demonstrated the successful use of virgin local limestone in replacing imported gabbro in asphalt base course. Laboratory testing and site trials were conducted to confirm the successful use of limestone as an alternative to imported
gabbro. The local limestone was easier to lay and compact in practice on site with improved in-service performance (Rolt et al., 2010).

The fine aggregate obtained from CDW and EW is not likely to be suitable for use in asphalt because of the high water absorption and salt contents and the materials would fail the sand equivalent test and plasticity criteria.

4.3.2  **Incinerator bottom ash (IBA)**

4.3.2.1  **Quick guide**

- Requires weathering and washing before use to ensure volume stability and meet specification requirements;
- Potentially high sulphate and chloride contents, especially in fine aggregate;
- Low particle strength, high water absorption and high lightweight particles limit use in concrete and some unbound applications;
- May be suitable for use as unbound subbase, subject to trial;
- Niche application as partial replacement for coarse aggregate in concrete blocks.

4.3.2.2  **Typical properties**

Typical laboratory test results for coarse/all-in aggregate in concrete applications are given in Table 4-4. 28 day compressive strength and water absorption in trial mixes for C40 concrete are shown in Figure 4-2 and Figure 4-3.

The properties of IBA are generally inferior to those of CDW and EW; in particular the particle strength, as measured by the Los Angeles abrasion test, is significantly lower than for the CDW and EW and is close to the limiting value for unbound subbase and well above the limiting value for coarse aggregate in concrete and asphalt. IBA may be suitable as unbound subbase, but a subbase trial is required before it can be considered for inclusion in the Qatar Construction Specification.

IBA should not be used as backfill to concrete or metal structures because of high sulphate and chloride content.

IBA is not suitable for use as coarse aggregate in cement bound material as the cement may react with the sulphates and also with the silica in glass, aluminium and other metals, resulting in expansive reactions which could damage overlying structures or pavements.

Laboratory tests showed that IBA is not suitable for use as coarse or fine aggregate in concrete. However, it does show promise as a partial replacement for gabbro in concrete blocks at levels of up to 20%. This has been confirmed by the site trial in Doha in 2013, see Section 5.1. As the current production of IBA is fairly low – estimated at about 50,000 tonnes per year – this application may be able to absorb all the production.

IBA is unlikely to be of use in asphalt due to the low particle strength.
4.3.2.3 Issues

IBA is produced by combustion of household and commercial waste at about 850 °C. It is therefore out of equilibrium with the atmosphere and needs to be weathered before use. The weathering reactions can be complex and generally involve hydration of various phases. It is important to ensure that these reactions are complete and the aged material is volumetrically stable before use in construction. This may pose problems in a hot desert environment. There is a lot of experience in the weathering of IBA in temperate countries such as Europe and the USA, but less in climates such as Qatar. It will be necessary to develop protocols for weathering the IBA in Qatar before it can be considered for inclusion in the Qatar Construction Specification.

IBA can undergo a number of expansive reactions in construction applications. These can be due to formation of expansive sulphate minerals such as gypsum or ettringite or to reaction of glass, aluminium or metals with strong alkalis in cement. The reactions with aluminium can generate hydrogen gas, with a risk of explosion if this is allowed to accumulate in a confined space. Care should therefore be taken in using IBA in concrete blocks to ensure that the area is adequately ventilated (UK Highways Agency, 2011).

Concerns have been expressed about leaching of metals and other salts from unbound applications of IBA, and there are restrictions on where they may be used in some countries. In the UK, for example, IBA is not permitted to be placed below the water table or above major aquifers. Leaching is not an issue if IBA is used in concrete blocks. However, if it is proposed to use IBA in unbound applications in Qatar it will be necessary to agree a protocol with the Ministry of Environment on where it can and cannot be used.

4.3.3 EAF Steel slag

4.3.3.1 Quick guide

- Requires weathering before use to ensure volume stability;
- Potentially suitable for wearing course of asphalt pavements because of high skid resistance;
- May also be suitable as railway ballast;
- Concerns about volume stability may limit use in concrete and cement bound material;
- Concerns about radioactivity and leaching have to be addressed.

4.3.3.2 Typical properties

Typical properties for steel slag and ancient river gravel, with imported gabbro as a control, are given in Taha et al. (2014) for unbound and asphalt applications. The results are reproduced as Table 4-6. Values in excess of limiting values in the Qatar Construction Specification (QCS 2010) are shown in yellow shading.

The steel slag complies with the requirements of the Qatar Construction Specification (2010) for all the parameters tested for unbound and asphalt applications. A number of
asphalt mixtures were satisfactorily produced using 100% steel slag and 50:50 blends of steel slag with river gravel and gabbro.

Steel slag generally possesses good resistance to polishing and gives an aggregate that is suitable for use in the wearing course of roads, which is a very high value application. Tests should be carried out to assess the skid resistance of the aggregate. If these are successful, site trials should be carried out.

Table 4-6 Properties of steel slag and river gravel (from Taha et al., 2014)

<table>
<thead>
<tr>
<th>Property</th>
<th>Unbound applications</th>
<th>Asphalt applications</th>
<th>Steel slag</th>
<th>River gravel</th>
<th>Gabbro</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>NA</td>
<td>NA</td>
<td>3.52</td>
<td>2.69</td>
<td>2.98</td>
</tr>
<tr>
<td>Water absorption</td>
<td>NA</td>
<td>≤1.5</td>
<td>1.06</td>
<td>1.12</td>
<td>0.34</td>
</tr>
<tr>
<td>Sand equivalent</td>
<td>≥25</td>
<td>&gt;30</td>
<td>41</td>
<td>33</td>
<td>47</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>≤6</td>
<td>≤6</td>
<td>Non-plastic</td>
<td>Non-plastic</td>
<td>Non-plastic</td>
</tr>
<tr>
<td>Flakiness Index (%)</td>
<td>≤35</td>
<td>≤25-30</td>
<td>1</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>Elongation Index (%)</td>
<td>≤40</td>
<td>≤25</td>
<td>13</td>
<td>26</td>
<td>24</td>
</tr>
<tr>
<td>Los Angeles abrasion (%)</td>
<td>≤40</td>
<td>≤25-30</td>
<td>15</td>
<td>23</td>
<td>8</td>
</tr>
<tr>
<td>Soundness – coarse</td>
<td>≤20</td>
<td>≤10-15</td>
<td>1</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Soundness - fine</td>
<td>NA</td>
<td>≤18</td>
<td>4</td>
<td>30</td>
<td>16</td>
</tr>
<tr>
<td>Soaked CBR (%)</td>
<td>≥80</td>
<td>NA</td>
<td>239</td>
<td>143</td>
<td>129</td>
</tr>
</tbody>
</table>

NA – no limiting value

Note: Highlighted cells indicate parameters which sometimes exceed the limiting values.

Tests were also carried out by Qatar University (Taha et al, 2013) on steel slag as partial replacement for gabbro coarse aggregate in concrete. The results are presented in an unpublished report for Qatar Steel which also contains the results for unbound applications and asphalt described above. The tests show that replacing gabbro with steel slag at 25%, 50%, 75% and 100% increased the compressive strength, tensile strength and flexural strength at 7, 28 and 90 days in concrete with a nominal strength of 30MPa. No long term tests to check for swelling potential were carried out.
4.3.3.3 Issues

Steel slag is known to be susceptible to swelling due to hydration of calcium and magnesium oxides, but no tests have been carried out to date to assess the swelling potential. A suitable test is given in BS EN 1744-1: 2012. Weathering is critical to elimination of the risk of swelling with steel slag, but the only information provided about the samples is that they were aged “between 1 and 8 years”. No tests for chemical properties such as sulphate, chloride or pH value were reported. This would affect how the slag could be used as an unbound material, as well as giving information on the extent of weathering. These aspects will need to be investigated before the slag can be used in construction.

Various environmental concerns have been raised about the use of steel slag, including the risk of radioactivity and potential leaching of contaminants. These issues should be resolved with the Ministry of Environment.

4.3.4 Other steel by-products

4.3.4.1 Quick guide

• Ladle slag probably similar to EAF slag;
• Limestone and dolomite probably suitable for a range of unbound applications, possibly also as concrete aggregate;
• Hydrated lime may be useful as a binder for hydraulically bound materials.

4.3.5 Ancient river gravel

4.3.5.1 Quick guide

• Difficult to separate the gravel from the matrix of sand with high gypsum content;
• Potentially suitable as coarse aggregate for concrete, subject to concerns about alkali silica reactivity being addressed;
• Also potentially suitable as backfill to structures, drainage and pipe bedding – applications for which CDW & EW are not particularly suitable;
• Suitable as coarse aggregate in asphalt, particularly in blends with other aggregates.

4.3.5.2 Typical properties

The deposits of ancient river sand that are exploited for concrete sand (Section 2) contain minor amounts of gravel. There are considerable quantities of this material still in the ground, plus large amounts that have been rejected as oversize material at the sand washing plants. However, the gravel particles are mostly still attached to the sandy matrix of the material, which in many cases is cemented by gypsum. Separating the
gravel from the matrix material will be a major challenge before the gravel can be exploited. However, some studies of the gravel have been carried out.

Properties of river gravel are given in Table 4-6, using test data from Taha et al. (2014). The material appears to be suitable for unbound applications and as coarse aggregate in asphalt. The gravel particles are very well rounded so would be more suitable as coarse aggregate in concrete rather than asphalt. Many of the particles consist of quartz, so the risk of alkali silica reaction will need to be assessed. Further testing and trials are recommended to determine the optimum use of the material.

Taha et al. (2014) reported the results of tests for concrete mixtures with gravel replacing gabbro at 25%, 50%, 75% and 100%. The results show a decrease in compressive strength, tensile strength and flexural strength compared to the gabbro, though all the mixes exceeded the design strength of 30 MPa at 28 days.

4.3.5.3 Issues

- Potential for alkali silica reaction if used in concrete;
- Will need extensive processing to separate the gravel from the sand and gypsum matrix of the material.
5 Case studies of use of recycled aggregates

Various authors have investigated the use of recycled materials in the Gulf States (Khan and Rasheeduzzafar, 1984; Ali et al., 2001 & 2002; Blanco-Carrasco et al., 2010; Al-Otaibi and El-Hawary, 2005; Al-Otaibi, 2007; Abdelfatah and Tabsh, 2011). Many countries are focusing on recycled concrete aggregate, which is proven to be practical for unbound applications, non-structural concretes and to a limited extent for some structural-grade concrete. In Abu Dhabi, crushed recycled concrete from demolition of buildings has been used in pavement construction and asphalt recycled back into new pavements (The National, 2012). However, the processing and quality control cost associated with their use plus the premium paid for mix design adjustment to achieve the same strength grade as concrete with natural aggregates can vary considerably. In all cases, availability and consistency of supply are prerequisites for the use of recycled aggregates.

The increasing rate of construction throughout the Gulf has led to greater pressure on sources of high quality primary aggregate, while generating large volumes of construction and demolition waste that is largely dumped. It is increasingly realised that this is environmentally and economically unsustainable, and more attention is being given to the production and use of recycled aggregates. Some case studies are given in the following sections.

5.1 Use of recycled aggregates and crushed rock fines in trial buildings, Qatar

Following the success of the laboratory trials (Section 4.3.1.4), a site trial was carried out to see if it was possible to produce and use concrete and blocks using recycled aggregates in building applications. The trial was also used to assess the potential conservation of washed sand by partially replacing with crushed limestone fines in structural concrete.

The trial consisted of three small single-storey buildings and was erected in the Ashghal premises at Najma Street in Doha. The structural design of the trials was carried out by local consultant Khatib and Alami. The three buildings are 2.5 m x 2.5 m in plan. All rooms consist of a roof, roof beam, column and strip footing beam. The internal finishing slab is made up of a 150 mm slab on grade. The recycled aggregates were used to replace different proportions of natural aggregate in structural (C40) concrete and non-load bearing concrete blocks (average 7.0 MPa). Details are given in Table 5-1.

Table 5-1 Composition of concrete and blocks in site trial

<table>
<thead>
<tr>
<th>Material</th>
<th>Building 1</th>
<th>Building 2</th>
<th>Building 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C40 concrete</strong></td>
<td>50% EW (replacing Gabbro)</td>
<td>Control (100% Gabbro and 100% washed sand)</td>
<td>60% Crushed rock fines (replacing washed sand)</td>
</tr>
<tr>
<td><strong>Concrete blocks</strong></td>
<td>50% CDW (replacing Gabbro)</td>
<td>Control (100% Gabbro and 100% washed sand)</td>
<td>20% IBA (replacing Gabbro)</td>
</tr>
</tbody>
</table>
The EW and CDW were obtained from Rawdat Rashid and the IBA from the Domestic Solid Waste Management Centre (DSWMC) near Masaieed. The production of ready mix concrete mixtures was carried out in the ReadyMix Qatar concrete plant in Masaieed, whereas the concrete blocks in Khalid Cement Industries Complex in the Industrial area of Doha.

Hollow concrete blocks (400x200x200 mm) were manufactured for use as external non-load bearing walls with a minimum compressive strength of 7.0 MPa, as per the requirement of the Qatar Construction Specification (2010). The blocks were tested for compressive strength in accordance with BS EN 771-3 (2011). The test results are shown in Table 5-2. The results comfortably met the specification requirements, although the CDW and IBA gave lower values than the gabbro control.

### Table 5-2 Compressive strength results for concrete blocks

<table>
<thead>
<tr>
<th>Material</th>
<th>Average strength (MPa)</th>
<th>Minimum strength (MPa)</th>
<th>Maximum strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDW (50%)</td>
<td>9.9</td>
<td>9.19</td>
<td>10.4</td>
</tr>
<tr>
<td>IBA (20%)</td>
<td>9.0</td>
<td>8.4</td>
<td>9.71</td>
</tr>
<tr>
<td>Control (gabbro)</td>
<td>11.0</td>
<td>9.34</td>
<td>13.97</td>
</tr>
<tr>
<td>QCS 2010</td>
<td>7.0</td>
<td>5.6</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Three different concrete mixtures were used with the composition given in Table 5-3.

### Table 5-3 Concrete mix design for trial

<table>
<thead>
<tr>
<th>Parameter</th>
<th>C40 Control</th>
<th>C40 50%EW</th>
<th>C40 60% CRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg)</td>
<td>370</td>
<td>370</td>
<td>335</td>
</tr>
<tr>
<td>Gabbro 20mm Aggregates (kg)</td>
<td>719</td>
<td>360</td>
<td>735</td>
</tr>
<tr>
<td>Gabbro 10mm Aggregates (kg)</td>
<td>480</td>
<td>240</td>
<td>489</td>
</tr>
<tr>
<td>Excavation waste (15-20mm) (kg)</td>
<td>0</td>
<td>64</td>
<td>0</td>
</tr>
<tr>
<td>Excavation waste (5-15mm) (kg)</td>
<td>0</td>
<td>458</td>
<td>0</td>
</tr>
<tr>
<td>CRF Limestone sand (kg)</td>
<td>0</td>
<td>0</td>
<td>475</td>
</tr>
<tr>
<td>Washed sand (kg)</td>
<td>750</td>
<td>750</td>
<td>325</td>
</tr>
<tr>
<td>Chemical admixture (l)</td>
<td>3.53</td>
<td>4.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Total water (l)</td>
<td>181</td>
<td>191</td>
<td>177</td>
</tr>
<tr>
<td>Water to cement (w/c)</td>
<td>0.446</td>
<td>0.446</td>
<td>0.446</td>
</tr>
</tbody>
</table>
The site construction was carried out by local contractor Qatari Arabian Construction Co. Construction commenced in early May 2013, where average daytime temperatures generally reached around 39°C and the average minimum temperature dropped at night to around 27°C. Construction was completed by the middle of June 2013.

The delivery time from the plant to site ranged from 64 to 89 minutes, with an average of 74 minutes. Slump values ranging from 210 to 230 mm were obtained at the ReadyMix plant with an average value of 220 mm. On site the slump ranged from 140 to 200 mm with an average of 170 mm. The average slump reduction between tests carried at plant and site was 23%. Despite the average 74 minutes delivery time, the concrete maintained adequate workability to be poured and compacted to the required standards.

Figure 5-1 Construction of site trial

Figure 5-2 Completed trial buildings
The construction of the site trial is illustrated in Figure 5-1 and the completed buildings in Figure 5-2; building 1 is on the left, building 2 in the middle and building 3 on the right (Table 5-1). In addition to the concrete buildings, concrete elements were prepared to demonstrate the potential use of concrete made with recycled aggregate in various applications that are commonly used in the construction industry in Qatar. Soakaways, crash barriers, and concrete beams were constructed; some of the soakaway elements can be seen in Figure 5-2.

The buildings were constructed successfully and have shown no signs of deterioration to date (January 2015). The performance of the buildings was monitored for one year through tests on cubes and cores. The cube compressive strength for the three concrete mixtures up to the age of one year is given in Figure 5-3. The results show that replacing 50% of the imported gabbro with EW aggregate increases the compressive strength by approximately 10%. Greater improvement of approximately 30% is achieved by replacing 60% of the washed sand with crushed rock fines.
Figure 5-4 Core compressive strength of concrete from trial

A similar strength trend is obtained from the core compressive strength as shown in Figure 5-4 at 28 and 365 days. The EW concrete gave a slightly higher strength whereas the CRF considerably increased the strength when compared to the control concrete. The strength results clearly indicate that recycled aggregate can easily achieve similar strength properties to the concrete made with imported gabbro.

The durability of concrete was assessed by testing water absorption (BS 1881-122) and water penetration (BS EN 12390-8), as per the QCS 2010, and the results are presented in Figure 5-5. As expected, the more porous nature of EW aggregate resulted in the highest water absorption value as shown in the water absorption results. However, the absorption value of the EW at 28 days is 2.5% which is the maximum level required in the QCS 2010 for durable concrete. The effect of EW and crushed rock fines on improving the packing of concrete ingredients and reducing its permeability is illustrated in the water penetration results. Both EW and CRF concrete gave lower water penetration values than the control concrete made with imported gabbro aggregate.

In general, the strength and durability-related properties of the buildings trial gave satisfactory performance for the use of recycled aggregate and crushed rock fines in structural concrete and concrete blocks, compared to the control building constructed with primary gabbro aggregate. The results should give more confidence on the use of recycled materials and thus recycled aggregate could potentially be used in a wide range of applications.
One of the main reasons for the success of the project was the collaboration between a wide range of stakeholders, including various government departments, research organisations, Qatar University, design consultants, concrete and block producers, suppliers of primary and recycled aggregate, and building contractors. All parties addressed the practical issues of how the materials were to be produced and used in a positive and constructive manner. This illustrates that many of the issues commonly raised as obstacles to use of recycled aggregates can be successfully overcome and is an encouraging example for the wider use of these materials in Qatar.

5.2 Use of recycled aggregates as unbound subbase, Rawdat Rashid

To demonstrate the suitability of recycled aggregates produced from excavation waste and construction and demolition waste as unbound subbase in Qatar, a trial road was constructed and subjected to a trafficking trial in October 2014. The trial road consisted of three sections each of 120 m length, comprising recycled aggregates produced directly from excavation waste (EW) and crushed concrete (RCA) plus a control section of EW with about 20% dune sand added, reflecting local practice of adding dune sand to limestone to produce a material meeting the requirements for Class B unbound material in the Qatar Construction Specification, 4th edition (2010).

The trial road was constructed as part of a replacement access road the landfill site at Rawdat Rashid, and the recycled aggregates were produced at the facility operated by the Qatar Quarry company adjacent to the site. Construction was carried out by Boom Construction. The existing access road was removed and the new road constructed on a prepared natural subgrade of limestone. Two layers of unbound subbase were placed, with the first layer acting as a regulating layer to even out minor undulations in the subgrade. The second layer was of 150 mm thickness throughout. An 80 mm layer of asphalt was placed on top of the unbound subbase layers. The dimensions of the pavement are shown in cross-section in Figure 5-6.
The following in-situ testing was carried out during construction:

- In-situ density by sand replacement (first and second layers of subbase);
- Lightweight deflectometer (subgrade, first and second layers of subbase).

Originally it had been planned to carry out in-situ CBR tests on the subgrade and both subbase layers. However, an initial in-situ CBR test on the subgrade showed that it was too strong for the equipment. The in-situ CBR test is designed for materials with relatively low CBR; however, laboratory tests on the subbase materials gave CBRs in excess of 100% (Table 4-3) and similar values were expected in-situ. The subbase material also contains a significant proportion of material coarser than 20 mm (Figure 4-1). However, the standard for in-situ CBR (BS1377-9) states that the test is only appropriate for material with a maximum particle size not exceeding 20 mm. It was therefore decided that the in-situ CBR test was not appropriate for either the subbase or subgrade materials. Instead, the stiffness of the materials was determined by means of the lightweight deflectometer test, which gives the dynamic deflection modulus (Evd).

The in-situ tests give a good indication of the performance of the materials. However, to assess the overall performance of the materials, it was decided to carry out a trafficking trial on the subbase before the asphalt layers were placed. The trafficking trial consists of subjecting the unbound layers to 1000 equivalent standard axles and measuring the rut depths produced. An equivalent standard axle is defined as having a load of 8160 kg. The equivalence factor (EF) for each axle can be calculated from the formula (TRL Overseas Road Note 40, 2004): \( EF = \left(\frac{\text{axle load in kg}}{8160}\right)^{4.5} \). This test is used in the UK as a method for assessing the performance of new materials; if the average rut depth is less than 30 mm the material is deemed to have passed the trial. The test method is set out in Series 800 of the UK Specification for Highway Works (Highways Agency et al., 2009). The trafficking trial was carried out in accordance with this specification.

Construction of the trial road took place between 15th October and 1st November 2014. The placing and compaction of the first layer of recycled aggregates derived from excavation waste is shown on Figure 5-7 and the compacted surface of the sections of crushed concrete and excavation waste plus dune sand on Figure 5-8.
Figure 5-7 Placing and compacting first layer of trial road

Figure 5-8 Compacted surface of crushed concrete and excavation waste with dune sand

The in-situ sand replacement density test and lightweight deflectometer test are shown on Figure 5-9. The sand replacement density tests were carried out by ACES and DTL, and the lightweight deflectometer tests were carried out by Ashghal.

Figure 5-9 Sand replacement density and lightweight deflectometer tests

The in-situ density tests indicated relative compaction was less than 100%, and for some tests it was less than 95%. The Qatar Construction Specification requires dry density to be at least 100% of the laboratory values. The reasons for this are not clear, as the
material appeared to be well compacted by suitable plant and the trafficking trial indicated very satisfactory performance.

The dry density depends on the moisture content as well as the bulk density. The trial was carried out during the second half of October, when temperatures were well above 30°C for most of the time. The materials were mixed with water to bring them to the required moisture content immediately before placing. Consequently the materials began to dry out rapidly after compaction. This could be visibly observed by changes in colour during the day, particularly for the RCA material. The materials were sometimes watered after compaction, to reduce dust. As a result the moisture content, and hence the dry density, were not fixed values, as shown in Table 5-4. This shows the average as-placed moisture content, taken from samples from the paver, the average moisture content in the sand replacement tests, generally taken the day after compaction, and the corrected optimum moisture content for the three materials from laboratory tests.

All of the materials were wet of optimum moisture content when placed but were dry of it by the time the in-situ density tests were carried out. The EW and RCA materials are slightly over 2% wet of optimum when placed, and about 1.5% dry in the in-situ density tests. The EW + DS material shows less variation in moisture content, with a total variation of less than 1%. The high initial moisture content may be the reason for the relative compaction being less than 100%. Given the climate of Qatar it will be necessary to add water to fill materials almost all the time to achieve moisture content close to optimum. The amount of water added is down to the skill and experience of the workforce involved. Recycled aggregates normally have higher values of optimum moisture content than natural aggregates, as they usually have higher values of water absorption. This is particularly the case for the crushed concrete. Lack of familiarity with recycled aggregates, and hence misjudgement of the amount of water to add, may be the cause of the failure to achieve 100% of the maximum dry density. Greater experience with recycled aggregates should result in less over-addition of water. However, given the current methods for adjusting moisture content and the speed with which materials dry out, some error is almost inevitable.

<table>
<thead>
<tr>
<th>Material</th>
<th>As-placed moisture content (%)</th>
<th>In-situ density test content (%)</th>
<th>Corrected optimum moisture content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation waste</td>
<td>9.6</td>
<td>5.8</td>
<td>7.1</td>
</tr>
<tr>
<td>Crushed concrete</td>
<td>11.4</td>
<td>7.3</td>
<td>9.0</td>
</tr>
<tr>
<td>Excavation waste plus dune sand</td>
<td>5.8</td>
<td>4.7</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Lightweight deflectometer tests, presented in Table 5-5, showed an increase in dynamic deflection modulus from layer 1 to layer 2, but no significant difference between the three materials. Comparison of the results with UK design guidance for pavement design, IAN73/06, indicates that all three materials in layer 2 would be classed as a Class 2 foundation, suitable for use up to traffic levels of 80 msa. The materials in layer
1, placed directly on the subgrade and of more variable thickness than layer 2, would be classed as a Class 1 foundation, suitable for use up to 20 msa. Layer 1 is in effect a regulating layer, what would be classed as capping in the UK, whereas layer 2 is a true subbase layer and illustrates the potential of the materials.

A trafficking trial was then carried out using the procedure set out in the 800 Series of the UK Specification for Highway Works. The subbase was subjected to 1000 equivalent standard axles, which equated to 175 passes of a loaded lorry provided by the Qatar Quarry Company (Figure 5-10). The average and maximum rut depths in each material and for the trial overall are shown in Table 5-6. Rut depth averaged less than 10 mm in each section, well within the limiting value of 30 mm in the Specification for Highway Works. The measured rut depths confirm the visual impression that the materials stood up to the applied loading very well with very little deformation.

![Figure 5-10 Trafficking trial in progress, October 2014](image)

All three materials performed well. No significant differences were found in the performance of the three materials. This suggests that the key parameters for assessing performance are grading and those relating to particle strength and durability, namely Los Angeles abrasion value, soundness and soaked CBR. The index properties such as Sand Equivalent, Liquid Limit and Plasticity Index, which vary greatly between different laboratories even for the same material, appear to be less significant, at least so long as the materials remain above the water table. This supports the proposal to relax the limiting values for Liquid Limit and Plasticity Index to those suggested in TRL Overseas Road Note 31 for arid and semi-arid areas (55% for Liquid Limit and 20% for Plasticity Index), and to do away with requirements for sand equivalent for unbound materials altogether.

The trial was very successful overall and clearly demonstrated that recycled aggregates produced from excavation waste and crushed concrete can perform well as unbound subbase. The road was opened to traffic on 29th November 2014 and its condition will continue to be monitored.
### Table 5-5 Lightweight deflectometer test results

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Average dynamic deflection modulus $E_{vd}$ (MN/mm²)</th>
<th>Minimum dynamic deflection modulus $E_{vd}$ (MN/mm²)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subgrade</td>
<td>Limestone – EW section</td>
<td>68.17</td>
<td>50.10</td>
<td>13.98</td>
</tr>
<tr>
<td></td>
<td>Limestone – RCA section</td>
<td>67.73</td>
<td>49.60</td>
<td>16.76</td>
</tr>
<tr>
<td></td>
<td>Limestone – EW + DS section</td>
<td>83.55</td>
<td>49.90</td>
<td>29.75</td>
</tr>
<tr>
<td>Subbase layer 1</td>
<td>EW</td>
<td>82.47</td>
<td>70.80</td>
<td>6.62</td>
</tr>
<tr>
<td></td>
<td>Crushed concrete</td>
<td>61.68</td>
<td>43.00</td>
<td>20.51</td>
</tr>
<tr>
<td></td>
<td>EW + DS</td>
<td>65.85</td>
<td>39.10</td>
<td>16.62</td>
</tr>
<tr>
<td>Subbase layer 2</td>
<td>EW</td>
<td>107.20</td>
<td>70.30</td>
<td>23.76</td>
</tr>
<tr>
<td></td>
<td>Crushed concrete</td>
<td>109.43</td>
<td>87.60</td>
<td>24.11</td>
</tr>
<tr>
<td></td>
<td>EW + DS</td>
<td>105.10</td>
<td>90.00</td>
<td>10.61</td>
</tr>
</tbody>
</table>

### Table 5-6 Rut depths after trafficking trial

<table>
<thead>
<tr>
<th>Material</th>
<th>Average rut depth after 1000 ESAL (mm)</th>
<th>Maximum rut depth after 1000 ESAL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EW</td>
<td>7.5</td>
<td>11.0</td>
</tr>
<tr>
<td>Crushed concrete</td>
<td>7.4</td>
<td>11.0</td>
</tr>
<tr>
<td>EW + DS</td>
<td>0.4</td>
<td>6.0</td>
</tr>
<tr>
<td>Overall</td>
<td>4.8</td>
<td>11.0</td>
</tr>
</tbody>
</table>
5.3 Abu Dhabi Green Road

Abu Dhabi’s Department of Transport (DoT) has announced that it will build the first green road in the Middle East, which will connect the capital to Dubai. The five-kilometre pilot project will link the existing Abu Dhabi- Dubai main road (E11) and the new Abu Dhabi-Dubai main road (E311). The construction of the green road is expected to begin in the first quarter of 2015.

The project will act as a model for future roads to be built in the capital and will adopt globally accepted standards of sustainable practices, the DoT said. Environmentally friendly materials such as recycled asphalt, concrete aggregates and scrap rubber tyres will be used for the construction of the Middle East’s first green road.

“The Green Road project is one of the strategic initiatives undertaken by the DoT to attain the Surface Transport Master Plan vision and its priorities by developing an integrated road network that addresses the current and future needs of Abu Dhabi whilst setting an example of environment-friendly projects,” the department said in a statement.

Abu Dhabi’s Surface Transport Master Plan aims to improve the capital’s infrastructure by expanding roads and creating additional means of public transport.

The department is collaborating with international institutes and consultants along with strategic stakeholders such as the Urban Planning Council (UPC), Estidamma Programme Team, and the Environment Agency in Abu Dhabi and Masdar for the construction of the green road.

“Upon completion of the Green Road pilot project, the outcomes will be evaluated, analysed and used to improve the set guidelines as well as a rating system for future implementation of green roads throughout the Emirate of Abu Dhabi,” said the department.


5.4 Recycled Crushed Aggregate in Abu Dhabi

The green road is a visible outcome of the Order issued by the Executive Council of the Emirate of Abu Dhabi, under decree number 57/2012, requiring the mandatory use (subject to availability) of a minimum 40% aggregate (by volume) of recycled construction and demolition waste in suitable roadway infrastructure projects. The key material to achieve this target is Recycled Crushed Aggregate, defined as clean, hard, durable, angular fragments of rock, concrete and sand of uniform quality derived from construction and demolition (C&D) waste.

To enable the use of Recycled Crushed Aggregate, the Abu Dhabi Centre for Waste Management produced a standard entitled “The Recycled Crushed Aggregate Specifications for Base Course and Subbase” which was issued by the Chairman of the Department of Municipal Affairs in March 2012. The Abu Dhabi Quality & Conformity Council has set up a certification scheme for RCA in Abu Dhabi, to provide assurance to customers that the RCA will meet the performance requirements for unbound base and subbase layers in roads. The scheme was launched in December 2013.
The procedure followed by Abu Dhabi could provide a useful model for setting a reasonable but stretching target, updating the specification to enable the use of alternative aggregates and introducing a quality scheme to provide assurance on consistency and quality of the products. The specification for road construction followed a trial use of Recycled Crushed Aggregate in a road built for the development of the Baniyas Sports Club, where Al Jaber Group was the contractor and AECOM was the consultant.

The Recycled Crushed Aggregates are produced at a facility at Al Dhafra operated by Thiess Services Middle East under an agreement with the Centre for Waste Management. About 1.2 million tonnes of Recycled Crushed Aggregate have been used in the construction of the Etihad Railway Phase 1 by contractor Al Jaber Group (see http://www.khaleejtimes.com/kt-article-display-1.asp?xfile=data/nationgeneral/2012/May/nationgeneral_May402.xml&section=nationgeneral). These examples are encouraging clients and contractors to use Recycled Crushed Aggregate in other projects.
6 Quality

6.1 Quality Management Systems

One of the main reasons given by clients, contractors and designers for not using recycled aggregates is concern about the quality and consistency of the materials. Visual images of unsorted construction and demolition waste in skips and on building sites give the impression that aggregates derived from the raw material will contain a lot of contamination in the form of wood, plastic, paper, metal, clay, vegetation and other undesirable substances (Figure 3-4). However, there is also a lot of clean excavation waste and concrete in the material sent to Rawdat Rashid, and high quality aggregates can be produced from this material (Figure 3-6). Qatar Quarry Company at Rawdat Rashid is currently producing a range of graded and single-size aggregates from this material by conventional crushing and screening techniques (Figure 6-1). Technology is available to remove contaminants from the mixed feedstock material during the aggregate production process, and the contractor is investing in this to enable processing more of the material already on site and that arriving at the site.

In order for a producer to convince potential users of the quality and consistency of the recycled aggregates, it is necessary to set up a suitable Quality Management System (QMS) and demonstrate that it is being implemented. Qatar Quarry Company has implemented a suitable QMS at Rawdat Rashid. The precise form of the QMS can be varied to suit the nature of the materials and operations at the site, but should contain as a minimum the following items:

- A formal QMS document or set of documents, which should be up-to-date, easy to use and cross-referenced where necessary;
- Evidence of regular review by management;
Recycled aggregates in Qatar

- Roles and responsibilities clearly defined;
- Acceptance criteria for incoming materials;
- Procedures for dealing with non-conforming incoming materials, e.g. lorries found to be containing asbestos when the material is tipped;
- Clear definition of the production processes and the products being produced, with reference to the Qatar Construction Specification and related standards;
- Any special measures required for specific materials (e.g. weathering procedures for slags and ashes);
- Clear programme of inspection and testing for all products, related to rate of production;
- Test results readily available for customers to view, ideally on a website;
- Procedures for dealing with non-conforming products and evidence that these are followed;
- Evidence that products are not released to the customer until test results show that they meet the specification requirements;
- Clear details of products on delivery tickets.

A similar QMS should be in place for all aggregate production, including natural aggregates. It is understood that there have been issues with variability in the properties of imported gabbro in recent years, which a robust QMS would have prevented. Natural rocks like gabbro and limestone are not uniform in terms of their mineralogical composition, structure or engineering properties. It is recommended that importers of primary aggregates require that their producers implement suitable QMS in the source quarries and provide evidence of the quality of the materials before they are shipped to Qatar.

In addition to the producers’ QMS, further confidence in recycled aggregates can be given to industry if the scheme is audited and check testing carried out on a regular basis by an independent body. This could be the government, through Qatar Standards, or a separate, independent organisation. The certification scheme described in Section 5.4 for Abu Dhabi may be a good example; the fact that this is run by the government has given industry confidence to use the recycled aggregates, whereas prior to the scheme uptake of recycled aggregates was very slow and the future of the plant at Al Dhafra was in doubt.

Recycled aggregates can be produced wherever significant quantities of construction, demolition and excavation waste are available. Processing plants could thus be set up at other locations in Qatar to take advantage of local sources, such as large volumes of excavation waste from Qatar Rail and the World Cup infrastructure projects. Each plant should operate under a similar QMS, and be audited by the same independent body, to ensure a uniform standard of quality of the products. This will ensure that good producers are not undercut by operators who do not process or test their products properly. It will also ensure that recycled aggregates do not become associated with poor quality materials; if this was allowed to happen, it would do lasting damage to the potential use of recycled aggregates in Qatar.
6.2 Quality of feedstock

It would also help the quality of recycled aggregates if construction, demolition and excavation waste was segregated at source, so that it arrived at Rawdat Rashid with much lower levels of contamination. Major improvements could be made to the quality of demolition waste by removing all ‘soft’ internal furnishings and fittings, such as timber walls and partitions and air conditioning equipment, before demolition. This is standard practice in many countries, and enables over 95% of the ‘hard’ materials – concrete, blocks, bricks and tiles – to be recovered as aggregate. It is much more efficient to remove these materials before demolishing a building than to separate them after demolition. However, this is not current practice in Qatar.

Construction waste can be highly variable in nature, including excavation waste, soil, packaging, damaged building products, offcuts and contaminated material. This material can be processed and recycled much more effectively if it is segregated into different categories on site rather than all mixed together. The precise waste streams will vary depending on the nature and stage of the construction project, with excavation waste dominant in the early stages and packaging, damaged materials and offcuts during the building and fit-out stages. As a minimum, segregation of waste should include the following categories:

- Inert: excavation material, concrete, blocks, brick, tiles, glass, etc.;
- Hazardous: solvents, additives, glue, chemicals, contaminated soil, etc.;
- Non-inert: topsoil, vegetation, plasterboard, wood, plastic, paper, packaging, metal, rubber, etc.

The non-inert fraction can be further segregated where appropriate.

Waste associated with construction is the largest waste stream in Qatar, accounting for over 78% of the total according to figures from the Ministry of Development, Planning and Statistics. The disposal of vast quantities of this material are causing degradation of the environment over a large and increasing area at Rawdat Rashid. It is therefore important that as much of this material as possible is recycled, and that, over time, the existing deposits can be processed and the environment restored. This will also contribute to the rising demand for aggregate in the run-up to 2022.

To help change construction practices in Qatar and improve the amount of recycling, Codes of Practice have been developed for Construction and Demolition Waste, incorporating the principles described above. These are currently under consultation, with the intention of issuing them formally by summer 2015. The Draft Codes are included as Appendix A and Appendix B to this document.

6.3 Requirements for other materials

Construction, demolition and excavation waste are basically inert materials, so long as biodegradable contaminants such as wood, paper, plastic and vegetation are removed. However, steel slag and incinerator bottom ash are materials that have been produced at very high temperatures, and hence are out of equilibrium with the natural environment. Both materials contain mineral phases which absorb water and are liable to cause swelling reactions, which can cause damage to construction materials. It is therefore important that they are allowed to weather until these reactions have reached
a stable condition before they are used in construction. Tests are available to measure the swelling potential of steel slag (BS EN 1744-1).

An important part of the weathering process is the hydration of materials such as unslaked calcium and magnesium oxides in steel slag and glassy matrix materials in incinerator bottom ash. This poses particular problems in a desert environment such as Qatar, with very low and unpredictable rainfall. In countries such as the UK, weathering of steel slag is accelerated by maintaining it in a moist condition with high pressure steam. This is justified by the high value of the end product, which is used as aggregate in surface dressing for asphalt pavements.

At present, neither the steel slag nor the incinerator bottom ash is used in construction and no measures are taken to accelerate the rate of weathering. If it is proposed to use these materials in construction, it will be necessary to develop a protocol for weathering to ensure that they will not give rise to swelling or other undesirable chemical reactions. Experience of these materials should be sought from elsewhere in the Gulf to see which procedures are most effective. Trials should then be carried out to check that the procedures work satisfactorily in Qatar. The procedures should then be included in the QMS for the materials.

Various environmental concerns have been raised about the use of steel slag and incinerator bottom ash, including concerns about radiation from steel slag and leaching of metals and other contaminants from both materials. These should also be investigated, and any necessary treatments included in the QMS.


7 Standards and specifications

The use of aggregates in construction in Qatar is governed by the Qatar Construction Specification. The 4th edition of the QCS (2010) included very limited provision for the use of recycled aggregates. However, it has been extensively revised and updated and a new 5th edition was published in early 2015. This includes much greater provision for recycled aggregates in a range of applications, including earthworks, unbound pavement materials, cement bound materials, asphalt and concrete. In a number of applications, there are limits on the proportion of recycled aggregate, e.g. as coarse aggregate in concrete. The applications where recycled aggregates are permitted and, where relevant, the proportion of recycled aggregate permitted, in the 2014 edition of the Qatar Construction Specification are shown on Table 4-1 and Table 4-2 and summarised in Table 7-1.

Table 7-1 Permitted use of recycled aggregates in the Qatar Construction Specifications (5th edition, 2014)

<table>
<thead>
<tr>
<th>Application</th>
<th>Source Material</th>
<th>Maximum Replacement Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unbound subgrade and subbase</td>
<td>Excavation waste and demolition waste</td>
<td>100%</td>
</tr>
<tr>
<td>Blocks</td>
<td>All</td>
<td>100%</td>
</tr>
<tr>
<td>Non-structural concrete up to C25</td>
<td>Construction, demolition and excavation waste</td>
<td>20%</td>
</tr>
<tr>
<td>Non-structural concrete up to C40</td>
<td>Excavation waste and crushed concrete</td>
<td>50%</td>
</tr>
<tr>
<td>Structural concrete up to C30</td>
<td>Excavation waste and crushed concrete</td>
<td>20%</td>
</tr>
</tbody>
</table>

The new edition of the Qatar Construction Specification will make much wider use of recycled aggregates possible in Qatar. If accompanied by a robust Quality Management System (Section 6), customers will have confidence in the materials. The Qatar Construction Specification includes requirements for certification of all construction products, including aggregates. This scheme is operated by Qatar Standards. It is anticipated that producers of recycled aggregates will be included in this scheme in the near future, which will give further confidence to potential purchasers that the materials will be fit for purpose.

Currently, recycled aggregates are used mainly in unbound applications, particularly as subbase materials. In these applications they are largely competing with local limestone. The recycled aggregates are relatively cheaper than the limestone, and it is expected that their use in unbound applications will continue to grow. The recycled aggregates can be used in exactly the same way as the limestone in unbound applications, so industry does not have to make any changes to existing practices in order to use them.
The situation with use of recycled aggregates in concrete and asphalt is more complex. Recycled aggregates will be significantly cheaper than imported gabbro; however, to be able to use recycled aggregates in these applications, industry will need to make changes to existing practices. Batching plants for concrete and asphalt will need to install storage and facilities for mixing primary and recycled aggregates in blends, and mix designs will need to be altered to accommodate the different properties of the recycled aggregates, in particular higher water absorption and lower particle density. This will require initial expenditure of cost and time to put these systems in place. While the cost savings from the lower cost of recycled aggregates should lead to the initial outlay being rapidly recovered, lack of space may prove a barrier for some producers.

The 2014 edition of the Qatar Construction Specifications includes changes that enable the use of blends of washed sand and crushed rock fines as fine aggregate in concrete (Section 5.1). This is necessary because the available reserves of local sand are rapidly being used up, and will run out by the end of 2016 if measures are not taken to extend them. It is anticipated that the use of blends of washed local sand and imported crushed rock fines will be available as the principal form of fine aggregate in Qatar shortly. This will also require changes to mix designs and storage and batching facilities to be carried out, concurrently with the changes for use of recycled aggregates.

Current practice in the Middle East is not to use recycled aggregates at all in structural concrete, and only to a small extent in low strength concrete. The design philosophy has been to use only fresh, clean, hard primary aggregates with low sulphate and chloride content, such as the gabbro from the United Arab Emirates, in high performance applications (Walker, 2012). This approach is only sustainable if there is an adequate supply of suitable fresh rock; as indicated in Section 2, this is no longer the case given the increasing scale of construction in Qatar and elsewhere in the Gulf. Increasing cost and limited availability of natural aggregates will force many GCC countries to adopt the use of recycled aggregates in concrete and asphalt as well as in unbound applications.

In order to enable industry to adopt the use of recycled aggregates in concrete and other high value applications, design guidance will have to be provided. Considerable research on the use of recycled aggregate in concrete in the GCC countries has been carried out in academic and research institutions; however, there is limited experience in the practical application of the materials (Abdelfatah and Tabsh, 2011). This experience can only be gained by implementing the use of recycled aggregates in concrete and drawing together the results, particularly in relation to constructability and durability. Ongoing monitoring of case studies and updating of guidance documents will therefore be required to ensure the maximum benefit is gained from recycled aggregates without incurring risks to performance of the resulting concrete structures.

The Qatar Construction Specifications (5\textsuperscript{th} edition, 2014) is considered as the leading GCC specifications at a national level to permit the use of recycled aggregate in various construction applications, including high-value such as structural concrete. The changes are based on evidence of satisfactory performance from site trials and ongoing monitoring. It is envisaged that the experience from Qatar and elsewhere in the Gulf will be brought together into a unified GCC specification and related guidance documents in due course.
8 Areas where further work is required

A number of areas where further work is required have been identified:

- Assessing the influence of the clay mineralogy of limestone in Qatar on Liquid Limit, Plasticity Index and Sand Equivalent value and whether this indicates potentially harmful properties of the material;
- Assessing the suitability of recycled aggregates as coarse aggregate in cement and other hydraulically bound materials, in particular the risk posed by sulphates and chlorides;
- Investigate the potential of EAF steel slag for asphalt, concrete and railway ballast;
- Investigate the potential for extracting river gravel from ancient river sand deposits and potential use in concrete and other applications;
- Investigate weathering schemes for IBA and EAF steel slag;
- Investigate potential applications for weathered IBA;
- Investigating the use of crumb rubber in asphalt in Qatar;
- Reviewing requirements for measurement of in-situ CBR in coarse-grained soils. Investigate use of alternatives such as static plate loading tests or lightweight deflectometer tests;
- Reviewing the current requirement for the in-situ density of compacted subbase and road base to be at least 100% of the maximum dry density from laboratory tests. In particular, examine the effects of corrections for oversize material in coarse grained soils and the practicalities of achieving a moisture content close to optimum at the point of compaction;
- Develop requirements for the permissible amount of contaminants like wood, plastic and metal in recycled aggregates;
- Extend the range of mix designs for recycled aggregates in concrete and asphalt;
- Gather experience of the behaviour of recycled aggregates on a range of projects covering different types of construction – infrastructure, buildings, etc.
- Develop guidance based on this information and disseminate to industry and government;
- Certify recycled aggregate producers (and producers of natural aggregates) as part of the Qatar Construction Specification certification scheme;
- Review and update the Qatar Construction Specification in the light of these developments;
- Develop and implement Codes of Practice for construction and demolition waste to improve the quality of material arriving at Rawdat Rashid and to improve the management of waste in the construction industry in Qatar.
9 Summary and conclusions

The laboratory tests and site trials described in the previous sections have demonstrated that there is considerable potential for the use of recycled aggregates in Qatar, in particular recycled aggregates produced from the processing of construction, demolition and excavation waste. These could make a significant contribution to the demand for aggregates as unbound pavement materials and coarse aggregate in concrete and blocks over the next few years. Production of recycled aggregates at Rawdat Rashid is expected to have reached 2 million tonnes in 2014, rising to 6 million tonnes by 2016. Further increases in production are likely beyond 2016.

The revised edition of the Qatar Construction Specification in 2014 enables much greater use of recycled aggregates in a wide range of applications. It will also enable the use of blends of washed sand and crushed rock fines as fine aggregate in concrete. Qatar Standards will include recycled aggregates in their certification scheme to ensure that they meet the requirements of the Qatar Construction Specification. These measures will give industry confidence to use recycled aggregate in projects, particularly in unbound applications.

There is also potential for the use of steel slag and incinerator bottom ash in selected applications. However, these materials are not currently used in construction and protocols for weathering of both materials will have to be developed, to ensure that they do not give rise to swelling and other problems when used in construction.

Trials have shown that recycled aggregates derived from construction, demolition and excavation waste can be used successfully as coarse aggregate in concrete and concrete blocks. However, in order for this to happen on a large scale, mix designs will have to be revised and alterations made to batching plants to enable blends of recycled and primary aggregates to be used, as the Qatar Construction Specification limits recycled aggregates to 20% of the coarse aggregate in structural concrete. Alterations will also have to be made to mix designs and plants to accommodate changes in fine aggregate from washed sand only to blends of washed sand and crushed rock fines. The latter change is essential because reserves of suitable concrete sand in Qatar are rapidly diminishing, and will be exhausted by the end of 2016 if changes are not made. It is planned that these changes will be made by the end of 2015; ideally, the necessary changes to enable the use of recycled aggregates should be made at the same time. By contrast, recycled aggregates can be used in unbound applications in exactly the same way as natural aggregates. They are therefore more likely to be used in these lower value applications than in concrete or asphalt, at least initially.

It is clear therefore that significant changes to existing construction practice in Qatar will be required. This will affect all stakeholders. As more experience is gained with recycled aggregates in different applications, guidance documents and the Qatar Construction Specification will need to be updated. It is important that all stakeholders are aware of the impending changes, why they are necessary and what the implications are for them and for the construction industry as a whole.

The programme of development of recycled aggregates is part of a wider programme on construction waste, being undertaken as a result of the mid-term review of the Qatar National Development Strategy. This includes the development of Codes of Practice for Construction and Demolition Waste, designed to increase recycling of these materials. All these activities contribute to realising the Qatar National Vision of ensuring that economic growth is balanced by protection of the environment. Greater use of recycled
aggregates contributes to both aspects of the vision. Industry and government are therefore urged to utilise recycled aggregates wherever possible and encourage others to do the same.

10 Acknowledgements

The work reported in this document has been funded by the Qatar National Research Fund at the Qatar Foundation under National Priorities Research Programme (NPRP) project 4-188-2-061. The project has been supported by contributions from a number of organisations, whose help is gratefully acknowledged:

- Qatar Quarry Company at Rawdat Rashid for provision of samples, laboratory testing, assistance with the subbase trial including provision of the lorry for the trafficking trial, allowing us access to their Quality Management System and general advice and guidance on aggregate supply and properties in Qatar;
- Boom Construction for undertaking construction of the trial road and enabling the on-site testing and trafficking trial;
- Khatib and Alami for carrying out the design of the structures for the buildings trial;
- Khalid Cement Industries for carrying out trials of EW, CDW and IBA in concrete blocks and supplying blocks for the buildings trial;
- ReadyMix Qatar for production of the concrete incorporating EW, CDW and CRF for the buildings trial;
- Ashghal for support and advice throughout the project, in particular for allowing the buildings trial to be constructed on their site at Najma Street and for carrying out the lightweight deflectometer tests and arranging laboratory testing of as-placed materials for the subbase trial;
- David Matyus of Qatar Primary Materials Company for providing information on aggregate supply and demand and providing the CRF for the buildings trial;
- Sharon Ng Lay Har of The Ministry of Municipal Planning, Development and Statistics for provision of information and collaboration on the production of the draft Codes of Practice for construction and demolition waste;
- The Minister of Environment for supporting the project throughout;
- Mr Dave Gershkoff of TRL for carrying out the technical review of all reports for the project;
- Numerous colleagues in TRL, Qatar Standards, Qatar University and designers, contractors, suppliers and testing laboratories who have provided advice and support on numerous issues over the course of the project.
11 References


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Appendices
Appendix A  Draft Code of Practice for Demolition Waste

Introduction

This Code of Practice is issued by the Ministries of Environment, Municipality and Urban Planning and Development, Planning and Statistics, the Public Works Authority (Ashghal) and other organisations as listed and relates to new procedures to be followed by contractors undertaking demolition works in Qatar.

Objectives

Demolition contractors apply for permits to demolish specific buildings or structures from the Ministry of Municipality and Urban Planning (MMUP). The current practice is to demolish the buildings without removing fittings and other materials in advance. This results in demolition material with a high content of wood, plastic, metal and other contaminants. The demolition waste is taken to Rawdat Rashid landfill site. Only a small percentage of the waste, the material with the least contamination, is recycled as aggregate. The rest is dumped, leaving a large and increasing area polluted and degraded.

The purpose of the Code of Practice is to reduce pollution of the environment and maximise recovery of demolition materials by requiring contractors to remove the soft materials and fittings before demolition and segregate the waste arisings. The Code of Practice does not supersede existing health and safety requirements for demolition works.

Justification

The Code of Practice is introduced to help achieve the Qatar National Vision 2030 goal of “A Balance between Development Needs and Protecting the Environment” and the Qatar National Development Strategy target of recycling 38% of solid waste. Qatar’s construction sector is the main source of wastes in the state and accounted for 78.48% of the total wastes generated in 2012. Demolition works contribute a large proportion of this total. Action is needed to reduce the amount of waste and recycle it more effectively, in line with the Waste Management Hierarchy.

Maximising the amount of inert demolition waste that can be recycled as aggregate will help to meet national requirements for aggregate in the run-up to the 2022 World Cup. Producing recycled aggregates locally will cause lower emissions of carbon dioxide than importing them from neighbouring countries and will cost less, as well as providing employment for local people. The new requirements will thus provide social, economic and environmental benefits.

Actions required

- Prior to being granted a demolition permit, the contractor shall carry out a pre-demolition audit of the building/structure to be demolished. The pre-demolition audit will identify materials that can be removed for reuse or recycling, such as furnishings and fittings, false ceilings and floors, partitions, air conditioning units and other mechanical plant. The audit should also identify the possible presence of any hazardous materials such as asbestos. If necessary, specialist surveys should be carried out to establish whether hazardous materials are present and to identify the correct procedures for removing them prior to demolition.
- The pre-demolition audit should identify the main structural features of the building and enable an estimate of the total amount and nature of demolition waste to be made. The contractor should plan the demolition so as to maximise
the quantity of high quality, segregated material – clean concrete, blocks, bricks, etc. – that can be generated, as this will yield better quality recycled aggregates than mixed materials or materials contaminated with wood, plastic, paper, metal or other substances.

- Based on the results of the pre-demolition audit, the contractor shall prepare a waste management plan showing how he intends to handle materials before and during demolition so as to minimise contamination of the materials and achieve maximum value from reuse and recycling. The plan should indicate arrangements for storage and segregation of waste on site, a programme for demolition showing the various activities and an estimate of the likely quantities of different types of waste and where they will be sent for reuse, recycling or disposal.
- The contractor shall submit the pre-demolition audit, waste management plan and any specialist surveys that have been carried out to MMUP when applying for a demolition permit. MMUP will only issue a permit once the waste management plan has been approved.
- Demolition shall proceed in accordance with the programme shown in the waste management plan, subject to any changes required for health and safety reasons or due to discovery of unexpected materials or structural conditions.
- The contractor shall keep records of the quantities of different waste streams and where they were sent for processing, recycling or disposal. The records may be in paper or electronic format. The records should be available for inspection at the site office during the demolition works and should be kept at the contractor’s main office for a minimum of two years after completion of the work.
- The destinations of the various waste streams shall not change from those set out in the waste management plan without approval from MMUP.
- MMUP will carry out spot checks on vehicles arriving at Rawdat Rashid and other waste treatment facilities to confirm that materials are being delivered to the correct destinations.

The operation of the Code of Practice is illustrated on Figure AAAA.
Flowchart to illustrate operation of the Code of Practice for Demolition Waste

- **Pre-demolition Audit**
  - Carried out by contractor

- **Specialist surveys required?**
  - Yes
  - Carry out specialist surveys, e.g. asbestos
  - No

- **Waste Management Plan**
  - Produced by contractor
  - Further surveys and/or revise Waste Management Plan

- **Approval by MMUP?**
  - Yes
  - Remove furnishings and fittings including asbestos if required
    - Segregate on site
  - Demolish structure in accordance with Waste Management Plan
    - Segregate on site
    - Keep records for two years
  - Outputs: Segregated waste streams for reuse or sent to Waste Transfer Stations for recycling or disposal

- **No**
  - Segregated concrete, blocks, brick, rubble, etc. sent to Rawdat Rashid for recycling as aggregate

Figure AAA Operation of the Code of Practice for demolition waste
Appendix B Draft Code of Practice for Construction, Refurbishment and Excavation Waste

Introduction

This Code of Practice is issued by the Ministries of Environment, Municipality and Urban Planning and Development, Planning and Statistics, the Public Works Authority (Ashghal) and other organisations as listed and relates to new procedures to be followed by contractors undertaking construction and refurbishment works in Qatar.

Objectives

Contractors apply for permits for new building and refurbishment of existing buildings from the Ministry of Municipality and Urban Planning (MMUP). Waste from the works consists of bulk excavation material, mainly limestone, in the early stages of projects and a mixture of packaging, damaged building products, off-cuts, formwork, empty containers and other materials during construction, and of internal fittings and furnishings from refurbishment projects. The bulk excavation waste is taken to Rawdat Rashid landfill site. Most of the construction and refurbishment waste is collected in skips, usually without any segregation of different waste streams, and is sent to waste transfer stations for recycling or disposal. Much of the waste ends up in landfill sites, where it causes pollution and degradation of the environment.

The purpose of the Code of Practice is to reduce pollution of the environment and maximise recovery of construction, refurbishment and excavation materials by requiring contractors to segregate the waste arisings to enable reuse and recycling of the waste wherever practicable. The Code of Practice does not supersede existing health and safety requirements for demolition works.

Justification

The Code of Practice is introduced to help achieve the Qatar National Vision 2030 goal of “A Balance between Development Needs and Protecting the Environment” and the Qatar National Development Strategy target of recycling 38% of solid waste. Qatar’s construction sector is the main source of wastes in the state and accounted for 78.48% of the total wastes generated in 2012. Action is needed to reduce the amount of waste and recycle it more effectively, in line with the Waste Management Hierarchy.

Maximising the amount of inert excavation and construction waste that can be recycled as aggregate will help to meet national requirements for aggregate in the run-up to the 2022 World Cup. Producing recycled aggregates and other materials locally will cause lower emissions of carbon dioxide than importing them from neighbouring countries and will cost less, as well as providing employment for local people. The new requirements will thus provide social, economic and environmental benefits.

Actions required

- Prior to being granted a permit for construction or refurbishment, the contractor shall prepare a waste management plan showing how he intends to handle materials and waste during the construction/refurbishment operations so as to minimise damage of the materials creation of waste. The plan should indicate arrangements for storage and segregation of waste on site, a programme for construction/refurbishment showing the various activities and an estimate of the likely quantities of different types of waste and where they will be sent for reuse, recycling or disposal.
- As a minimum, the contractor should segregate the following waste streams:
Recycled aggregates in Qatar

- Inert: excavation material, concrete, blocks, brick, tiles, glass, etc.;
- Hazardous: solvents, additives, glue, chemicals, contaminated soil, etc.;
- Non-inert: topsoil, vegetation, plasterboard, wood, plastic, paper, packaging, metal, rubber, etc.

- Good practice would include further segregation of non-inert waste into different categories for ease of recycling, such as wood, plasterboard, metal, plastic and vegetation;
- The contractor shall submit the waste management plan to MMUP when applying for a construction permit. MMUP will only issue a permit once the waste management plan has been approved. It is anticipated that in government projects, the relevant government body will review and approve the waste management plan before it is submitted to MMUP.
- Construction shall proceed in accordance with the programme shown in the waste management plan, subject to any changes required for health and safety reasons or due to discovery of unexpected materials or structural conditions.
- The contractor shall keep records of the quantities of different waste streams and where they were sent for processing, recycling or disposal. The records may be in paper or electronic format. The records should be available for inspection at the site office during the construction works and should be kept at the contractor’s main office for a minimum of two years after completion of the work.
- The destinations of the various waste streams shall not change from those set out in the waste management plan without approval from MMUP.
- MMUP will carry out spot checks on vehicles arriving at Rawdat Rashid and other waste treatment facilities to confirm that materials are being delivered to the correct destinations.

The operation of the Code of Practice is illustrated on Figure BBBB.
Figure BBBB Operation of the Code of Practice for Construction, Refurbishment and Excavation Waste