"Assessing the role and use of recycled aggregates (RAs) in the sustainable management of construction and demolition (C&D) waste via a mini-review and a case study".

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Abstract

Rapid industrial development, mega construction projects and increased immigration are some of the reasons that the State of Qatar has recently generated an unprecedented amount of construction and demolition (C&D) waste in the country. The State is racing towards the FIFA World Cup 2022, a fact that requires additional construction, for which is expected to increase the rate of waste generation. Compared to other regions, there are relatively few studies in literature that report on the C&D waste management issues of the country. The present work begins to address this gap by providing insights into the current state of C&D waste management practices in Qatar and by providing a mini-review on the benefits of using recycled aggregates (RAs); only recently allowed locally by Qatar Construction Standards (QCS). A SWOT analysis has been implemented, using data and information from various sources including governmental reports, industries, local waste management companies, as well as reported interviews with relevant stakeholders. Finally, several strategies were proposed and developed that could potentially be implemented by stakeholders and decision makers, so as to improve the current status by encouraging more sustainable and viable practices.

Keywords: C&D waste; circular economy; solid waste; Qatar; recycled aggregates; recovery and recycling

ABBREVIATIONS

approx.	Approximately
C&D	Construction & demolition
ca.	Circa (Latin term for “approximately” or “about”)
CE	Circular economy
DSWMC	Domestic solid waste management centre
EC	European commission
GHG	Greenhouse gas
GSAS	Global sustainability assessment system
LEED	Leadership in energy and environmental design
LAs	Local authorities
NA	Natural aggregate
NAC	Natural aggregate concrete
QCS	Qatar construction standards
QDVC	Qatar diar vinci construction
RAs	Recycled aggregates (i.e. aggregates of any quality made from C&D waste)
RAC	Recycled aggregate concrete (i.e. concrete made with recycled aggregates)
RCA	Recycled concrete aggregate (i.e. a subset of RA of sufficient technical quality for the manufacture of concrete)
SDGs	Sustainable development goals
SoC	Substances of concern
SWM	Solid waste management
TRL	Transport research laboratory
UN	United nations
WFD	Waste framework directive

Introduction

The concept of Circular Economy (CE) as a response to our unsustainable use of finite resources is gaining momentum, having received significant governmental, academic, and organizational attention in recent years (Dumlao-Tan and Halog, 2017; Ellen MacArthur Foundation, 2016; Ranta et al., 2018). In CE, products are kept in service for as long as possible and designed so that their component materials can be recycled with minimal energy input at the end of their life, eventually eliminating waste and its social impacts (Iacovidou et al., 2017; Velenturf and Purnell, 2017). The European Commission (EC) CE action plan links the relevant legislative proposals with the United Nations (UN) Sustainable Development Goals (SDGs) adopted in 2015, in particular Goal 12 regarding sustainable consumption and production (European Commission, 2016). The EC has classified construction and demolition (C&D) waste amongst the five priority areas where progress needs to be made towards a circular reality (with food waste, plastics, critical raw materials, and biomass and bio-based products being the other four) (European Commission, 2016).

The C&D sector is one of the major resource-consumers and waste-producers in our modern society, using –on average- more than 40% of the total raw materials extracted on a global scale (Krausmann et al., 2017), generating about 35% of the world's solid waste and accounting for approx. 33% of the total CO_2 and greenhouse gas (GHG) emissions (Peng, 2016; Schrör, 2011; Ürge-Vorsatz and Novikova, 2008; Yuan et al., 2012). With over 20 billion tonnes manufactured globally each year, concrete is the world's most widely used composite, thus producing similar quantities of C&D waste (Purnell and Dunster, 2009).

The definition and composition of C&D waste are not clearly defined, varying significantly due to the wide variety of materials and construction techniques in use (European Commission, 2018; Llatas, 2013). On average, it mostly consists of crushed concrete, gypsum, tiles and traces of wood, metals, bricks, asbestos, glass, plastic and cardboard (European Commission, 2018; Kucukvar et al., 2014).

Sustainable C&D waste management is still at a rudimentary stage in many countries, rendering landfilling the most common final destination of C&D waste (Marzouk and Azab, 2014; Silva et al., 2017). Numerous environmental, economical, technical and societal barriers have been reported in literature that restrict the circularity in the C&D sector (Dumlao-Tan and Halog, 2017; Esa et al., 2017; Mittal and Sangwan, 2014; Ranta et al., 2018; Ritzén and Sandström, 2017; Yuan, 2017). The lack of coherent recycled materials quality standards in the Waste Framework Directive (WFD 2008/98) has led most EU countries to fulfil the requirement to recycle C&D waste many times by diverting it to lower-grade applications; for instance, producing aggregates for road base and filling materials in road construction (BIO Intelligence Service, 2013; European Commission, 2008; Hu et al., 2013; Weil et al., 2006). This is known as “cascaded recycling” or “downcycling” (Allwood, 2014; European Commission, 2008; Huysman et al., 2015) and does not fully contribute to the CE way of thinking, as it lowers the quality and value of the recycled material.

The most common recycling practice for C&D waste is as a feedstock for the production of recycled aggregates (RAs) that can replace natural aggregate (NA) in various applications and provide a more sustainable alternative by avoiding landfilling of waste and depletion of NA resources. RA is mainly obtained via crushing and processing of previously used inorganic construction materials, and while it normally contains a high proportion of concrete, it may also contain bricks, tiles, metals, glass and other miscellaneous materials such as paper, plastic, wood, and other debris (Kisku et al., 2017). RA that is to be used to manufacture structural concrete must be of a specific quality, free from such contaminants, in particular sulphates (e.g. from plaster), clays (e.g. from bricks or tiles) or excessive fine material. Such aggregate is classified as recycled concrete aggregate (RCA) and careful control and monitoring of its quality is fundamental to ensure a high-performing concrete and ensure adequate properties, such as compressive strength and durability (Purnell and Dunster, 2009). RCA is generally derived from the crushing of isolated previously-used concrete structural elements. In general, unfamiliarity with RA and RCA and their use leads NA to be considered of higher quality; however, from a generic environmental point of view the impacts of RA/RCA are much lower than that of NA (Blengini, 2009; Blengini and Garbarino, 2010; Bovea and Powell, 2016; Ding et al., 2016; Estanqueiro et al., 2018; Hossain et al., 2016; Ortiz et al., 2010; Rosado et al., 2017; Silva et al., 2017; Vieira et al., 2016; Vilches et al., 2017), whereas when it comes to the economic viability of a C&D recycling plant, the scientific views are divided (Braga et al., 2017; Coelho and de Brito, 2013a; Nunes et al., 2007; Zhao et al., 2010).

RA contaminated by unsound materials such as mortar, metals or plastics results in an aggregate with diminished mechanical properties; contamination with chemical impurities, especially sulphates which disrupt the hydration of the concrete and clays which increase the water demand for a given workability (increasing the water-cement ratio, which controls the strength and durability properties of all concretes) will result in aggregates unsuitable for structural concrete (Ann et al., 2009; Behera et al., 2014; Butler et al., 2011; McNeil and Kang, 2013). Thus, applying several recycling techniques (selective demolition, more accurate sorting, etc.) is imperative in order to minimise the presence of contamination in the produced RA and especially RCA (de Juan and Gutiérrez, 2009; Estanqueiro et al., 2018). While in theory RA can be used as aggregate for structural concrete, in practice this is reserved for RCA and RA is used for other applications (Rafi et al., 2014; Rafi, 2018, 2019; Rafi et al., 2011). The use of RCA derived from concretes of unknown composition is restricted to characteristic strengths below 50 MPa, while RCA derived from concretes of known composition may be used in higher-strength concrete (Purnell and Dunster, 2009; WRAP, 2004).

The State of Qatar is a peninsula located on the southwest shore of the Arabian Gulf. It lies between latitudes 24° and 27°N and longitudes 50° and 52°E and possesses a hot desert climate. In 2017, Qatar's total population was approx. 2.6 million: 313,000 Qatari citizens and 2.3 million expatriates. In addition, the country has been undergoing rapid development and increased immigration over the last twenty years. Qatar is a high-income economy, backed by the world's third-largest natural gas and oil reserves.

Recent sources report than in the State of Qatar, C&D waste accounts for more than 75% of all solid waste generated (Reid et al., 2016). Several current mega construction and development projects (such as the Qatar Rail and Lusail City) are expected to create significant amounts of C&D waste, presenting challenges with regards to the removal, transport and reuse of excavated materials. In addition, the country continues its quest for fulfilling the ambitious targets set in Qatar's vision 2030 (GSDP, 2008). The Qatari Transport Research Laboratory (TRL) has recently completed a study of innovative uses of RA in construction, noting that use thereof has only been allowed by Qatar Construction Standards (QCS) since 2014 (QCS, 2014). With the increasing demand for aggregates in the run-up to the 2022 FIFA World Cup, maximising the use of RAs is of utmost importance and could potentially divert huge quantities of these materials from landfill, thereby reducing the carbon footprint by up to 50%, in relation to importing primary NAs (Clarke et al., 2017; Hassan, 2015).

Recognising the need for high quality recycling as an effort to increase circularity and recovery of resources from waste and reduce reliance on imports, via this research article, the authors attempt to delineate the Qatar current status on C&D waste and communicate, as well as highlight, the various opportunities and challenges of using RAs in general, and in this region, in particular (via a SWOT analysis).

Overview of C&D waste practices in Qatar; properties and significance of the use of RAs and recycled aggregate concretes (RACs)

Current status of C&D waste management in the State of Qatar

The phenomenal development rates of the Qatar C&D sector have compelled its construction companies to grapple with critical waste management issues, especially over the last 5 years and in the run up to the 2022 World Cup. According to estimates from the Qatar Ministry of Environment, the C&D sector was responsible for approx. 56% of the generated waste in 2015 (11.7 kt out of the 21 kt generated on a daily basis) (MDPS, 2017). The majority of it was composed from excavated soil and sand, concrete and other mixed non-hazardous waste.

Current C&D waste management practices in the State of Qatar lag behind both regional, as well as international benchmarks. This lag could be attributed to a number of reasons. Qatar lacks precise and detailed C&D regulations, directives and standards, therefore the construction industries do not have adequate references and guidelines. It was not until recently that the Global Sustainability Assessment System (GSAS) was implemented to a number of new construction projects and the use of RAs was allowed by the QCS (Kader, 2016; QCS, 2014). In addition, a study on green building rating systems performed in Qatar showed that scores from C&D waste management sub-criteria in both GSAS and Leadership in Energy and Environmental Design (LEED) are considerably different (Mohamed and Musharavati, 2016). For example, for new building constructions LEED requirements demand a minimum of 50% of the C&D waste produced from the construction site to be salvaged and/or recycled, while in GSAS the sub-criteria related to C&D waste management require only submitting the respective plan (Abulebdah and Musharavati, 2017). Consequently, there are neither any rigorous requirements nor any follow-ups to enforce them. In addition, the relative sub-criteria specify only that waste should be collected and removed from the construction site. No stringent requirements are in place to recycle or reuse any of the waste generated, nor are there pre-requisites or mandatory requirements for C&D waste management, which means this aspect of projects will not be evaluated. Considerations of environmental management issues that incorporate C&D waste management are thus not a priority with contractors when undertaking construction projects in Qatar (Abulebdah and Musharavati, 2017). For instance, huge projects like Qatar Rail and Lusail City create immense amounts of C&D waste; but the players involved in these projects are the least interested in removing, transporting or reusing any excavated materials; however, in 2015 the 23 contractors involved in the two aforementioned projects reported that approx. 3.5t of solid waste (steel, plastic, cardboard) and ca. 8,700l of waste oil were recycled, thus creating contradictions and ambiguities in the information obtained (Clarke et al., 2017). In this regard, the Transport Research Laboratory (TRL) conducted a study in 2017 concerning the use of RAs, suggesting it as a priority and as a mean to avoid the use of NAs and, thus reduce the carbon footprint by up to ca. 50% (Clarke et al., 2017; Hassan, 2015).

Some construction companies, such as Qatar Diar Vinci Construction (QDVC) who employ thousands of people and deals with mega-structure projects, do implement more sustainable environmental policies. The “green programme” of QDVC includes commitments to efficient waste management, mitigation of any potential environmental impacts, green procurement techniques, application of clean technologies, investing in R&D and conserving natural resources (QDVC, 2016). The company managed to reuse approx. 643 m^3 of excavated soil and concrete during 2014 and recycle more than 3Mt of metals, paper and plastic with the help of several other companies (Al Suwaidi Paper Factory, Doha Plastic, Lucky Group and Al Haya Waste Management) (QDVC, 2016).

Moreover, in tower blocks at the Pearl-Qatar area (a Riviera-style island), an ENVAC waste management system has been implemented able to transport up to 3,700t of commingled waste, on a monthly basis, via underground pipes to a transfer station and from there to the Domestic Solid Waste Management (DSWM) facility, at Mesaieed, south of Doha (Clarke et al., 2017). This facilitates the residents that mostly live in high-rise buildings that do not contain inbuilt recycling facilities. Unfortunately, in Qatar most tower blocks do not contain specific waste collection spaces or points on every floor; in some cases they don't even have temporary storage facilities for recyclable materials.

In order to take further steps towards a CE, the State of Qatar needs a multi- and inter-disciplinary waste strategy. It must encourage the elimination of waste from the system through design for reuse and refurbishment as well as improved resource recovery and recycling. It must also tackle the wasteful attitudes, thought processes and mind-sets that generate the waste in the first place; and, in turn, to replace them with the CE view of treating and thinking of "waste" as valuable resources. This implies that in the future, SWM technologies need to go hand in hand with tangible and sustainable programmes that encourage innovative solid waste elimination at source. To this end, social media platforms should be fully utilised in Qatar to propel waste to the top of the public agenda and get the subject of waste "trending". The recently formed environmental organisation Doha Oasis is one vehicle through which these ideas and innovations can be promoted (Dohaoasis, 2018).

Significance of RAs and RACs; how to enhance their mechanical and durability properties. A mini literature review

Generic properties of RAs and RACs

The concept of using RAs as an alternative for the replacement of NAs first emerged in England during World War II, where RAs were mostly used for pavement construction (CCANZ, 2011). The difference between RA and virgin aggregate is the hardened cement paste and/or mortar that remains attached to the individual coarse aggregate particles. It is the porosity of this material that causes the RA to have a higher water absorption capacity (Gómez-Soberón, 2002; Katz, 2003; Martín-Morales et al., 2011) which increases even more with an increase in the size of aggregate (Martín-Morales et al., 2011). The lower mechanical strength of the RACs in comparison to NAC may be partly attributed to this adhered layer of old mortar (Martín-Morales et al., 2011) and partly to the increased water-cement ratio necessitated by the increase of water absorption by the aggregate, which limits strength development during hydration. The durability of RACs depends mainly on the chemical properties of the RA/RCA, in particular the presence of sulphates and chlorides. Excessive chloride content may lead to corrosion of the reinforcement steel (Debieb et al., 2009; Nagataki et al., 2004), although the majority of RAs contains chloride in the acceptable range; in any case, a water immersion could be employed as a countermeasure (Debieb et al., 2009). Excessive sulphate will disrupt the hydration of the cement, causing unwanted expansion and cracking in the concrete. There are also other properties to consider, such as workability (slump test) or wet density that depend on various parameters of the aggregate (e.g. moisture content, size, shape, texture) (Debieb et al., 2010; Evangelista and de Brito, 2010; Henschen et al., 2012; Kou and Poon, 2013; Malešev et al., 2010). Since the porosity of RA is higher than that of the virgin aggregate, the workability of the RAC mix is lower than the NA's (given the same water content). However, the use of chemical admixtures commonly used with concrete such as super-plasticisers can increase the workability of RAC

(Matias et al., 2014) and can easily be used to reduce the water-cement ratio to a level where the effects of increased water-cement ratio on strength and durability can be eliminated.

Several studies have demonstrated that mixing RAs with various other industrial waste such as fly ash, coal bottom ash, blast slag, silica fume, plastics, rubber tyres, etc. can, in some cases, be proved beneficial (Arulrajah et al., 2016; Arulrajah et al., 2017; Bravo and de Brito, 2012; Figueiredo and Mavroulidou, 2010; Foti, 2011; Hansen and Lauritzen, 2004; Kasai, 2004; Kim and Lee, 2011; Kim et al., 2010; Meyer, 2009; Özkan et al., 2007; Park et al., 2009; Son et al., 2011) in much the same way as such admixtures have been extensively investigated for use in traditional concrete.

Below a short literature review is attempted on the various properties of RAC and how these are affected by the individual parameters-factors involved in the overall procedure.

Mechanical Properties

Compressive strength

The compressive strength of concrete is its most important property, and many other properties such as tensile/flexural strength, durability, permeability and stiffness are inferred therefrom. Variables that cause a change in compressive strength will normally induce a proportional change to these other properties. The same is true for RAC. The compressive strength of any concrete, including RAC, depends upon many factors, in particular the water binder ratio but also aggregate types, mixing ratios, properties of admixtures used and the age of the concrete; for RAC the different characteristics of RAs and e.g. the adhered mortar will also be important. It has been reported that an increase in the proportion of RA at the same w/c ratio leads to decrease in compressive strength, generally up to 10% lower than that of virgin aggregate concrete (González-Fonteboa and Martínez-Abella, 2008; Kou and Poon, 2008; Rahal, 2007). However, other researchers observed that the compressive strength of concrete remains unaffected, or increases slightly (up to 25%) with the replacement of NA by RA (Abd Elhakam et al., 2012; Etxeberria et al., 2007; Fonseca et al., 2011; Huda and Alam, 2015). In either case, the compressive strength of RAC can easily be adjusted to match that of NA concrete via the application of several common concrete mix design methods, such as usage of admixtures (Abd Elhakam et al., 2012; Kou and Poon, 2012; Limantono et al., 2016; Mukharjee and Barai, 2014; Oner et al., 2005; Vinay Kumar et al., 2017), increase in the cement content (Etxeberria et al., 2007; González-Fonteboa and Martínez-Abella, 2008) or usage of plasticizers (Tam et al., 2005; Tam and Tam, 2007, 2008).

Split tensile strength

The split tensile strength of RAC is dependent upon multiple factors, such as RA quality and replacement ratio, water-binder ratio, type of cement and curing age. Several studies report that split tensile strength decreases with an increase in RA replacement ratio (Abd Elhakam et al., 2012; Kou and Poon, 2013; Zega and Di Maio, 2011), although other researchers have found that for a replacement ratio of up to 30%, RAC's tensile strength is the same or even in some cases exceeds that of virgin aggregate concrete (Dilbas et al., 2014; Mas et al., 2012; Padmini et al., 2009; Pereira et al., 2012). In addition, the split tensile strength is improved as the curing age increases (Etxeberria et al., 2007; Kou and Poon, 2008; Sagoe-Crentsil et al., 2001), whereas the use of slag cement and the addition of super-plasticizers has also been reported to enhance the tensile strength of RAC by 25% (or more) (Dilbas et al., 2014; Mas et al., 2012; Pereira et al., 2012). Similarly to compressive strength, the tensile strength of RAC is generally lower than that of NAC. Nonetheless, many studies have demonstrated that the tensile strength tends to become constant as the replacement ratio reaches 100% (Abd Elhakam et al., 2012; Ryu, 2002).

Flexural strength

Flexural strength is closely related to tensile strength. It has been documented that the flexural strength of RAC decreases with an increase in the RA replacement ratio (Katz, 2003; Malešev et al., 2010; Padmini et al., 2009; Topçu and Şengel, 2004). The reduction in flexural strength of RAC, with regards to conventional concrete, is dependent on the target strength. The higher the strength of concrete, the higher the reduction in the flexural strength of RAC is, mainly due to the addition of RA (Limbachiya et al., 2000; Padmini et al., 2009).

Modulus of elasticity

Modulus of elasticity has been reported to be negatively affected by the incorporation of RA (Fonseca et al., 2011; Kou and Poon, 2013; Pereira et al., 2012; Zega and Di Maio, 2011). Curing has high impact on modulus of elasticity, whereas the use of high compressive strength parent concrete has also been shown to favour the elastic modulus. Other researchers reported that fly ash takes considerable time to show its effect on modulus of elasticity (Anastasiou et al., 2014; Corinaldesi and Moriconi, 2009; Kou and Poon, 2013), whereas the use of super plasticizers leads to increase of the elastic modulus (Corinaldesi and Moriconi, 2009; Pereira et al., 2012).

Durability properties

Durability of concrete (including RAC) is defined as the ability of concrete to withstand external environmental and physical pressure, as well as chemical reactions (Kisku et al., 2017). According to Domone and Illston (2010) it is the ability of a material to remain serviceable for at least the required lifetime of the structure of which it forms a part (Domone and Illston, 2010). There are various factors that affect the durability, such as mixing ratios (particularly the water-binder ratio, small increases in which can cause drastic increases in permeability), placing and curing methods and associated quality control, ingredients involved, etc. Usually the permeability of the concrete (which controls the rate at which carbonation occurs, water & air permeability, and chloride penetration) and its resistance to long-term deformation (owing to drying shrinkage and creep) are the main characteristics that determine its durability. Furthermore, degradation of concrete can be caused by static and dynamic external environments (e.g. shrinkage caused by drying, creep caused by long-term loading freeze-thaw cycles, accidental overloads) or internal chemical reactions (e.g. alkali-aggregate reaction). It is important to understand the difference between degradation of the concrete, and any diminution of its ability to protect steel in reinforced concrete. In this latter role, concrete must: resist the ingress of substances deleterious to the steel (particular water and chlorides) by remaining impermeable and not suffering excessive cracking; and retain its chemical characteristics – i.e. resist reduction of its alkalinity by reaction with CO_2 (carbonation) in the atmosphere – which prevent corrosion of the steel.

It has not been clearly documented in literature whether RAC possess a lower durability than that of natural aggregate concrete (NAC). It is known that the sulphate and/or clay fraction in many potential RAs renders them chemically unsuitable for durable concrete, which is why there are strict limits on which RAs can be used as RCAs. Any inherent additional durability issues caused by using RCA could potentially be improved by incorporating appropriate adjustments to mixing approaches and amounts of admixtures when preparing RAC. A short discussion on the different properties that influence durability is provided in the subsections below.

Carbonation depth

The carbonation phenomenon is mostly attributed to the interaction between atmospheric CO_2 and unhydrated $Ca(OH)_2$ in the hardened cement paste that binds concrete together. Carbonation reduces the buffering capacity of the pore solution in the concrete by converting the alkaline calcium hydroxide into calcium carbonate. As the alkali metals in the pore solution also react with carbon dioxide, this results in lowering of the pH. If the pH drops below 10, and the carbonation depth reaches the steel reinforcement, the steel may become depassivated, increasing the likelihood of corrosion. Due to the high porosity of many RAs the carbonation depth of RAC, compared to NA concrete at a given time, increases with an increase in the replacement ratio of NA with RA. Studies have shown an almost 100% increase in the carbonation depth of RAC samples where there has been a 100% replacement of virgin aggregate with RA (Debieb et al., 2009; Kou and Poon, 2013; Levy and Helene, 2004; Matias et al., 2014; Silva et al., 2015; Somna et al., 2012; Xiao et al., 2012; Zhu et al., 2013). The use of fly ash, as a partial replacement of cement, has been reported to increase the carbonation depth (Kou and Poon, 2012). High strength concretes will carbonate more slowly than low strength concretes (Purnell and Dunster, 2009). Other researchers reported that the addition of super plasticizers tend to lower initial carbonation rates in RAC compared with NAC; however, this effect fades with time and at the end carbonation of RAC exceeds that of NAC (Matias et al., 2014).

Long-term deformation

Long-term deformation of concrete refers to changes in: deformation additional to that induced by the initial loading; shape; and appearance of the existing cracks in concrete, without any increment in the external forces. It is usually assumed to be related to two parameters; drying shrinkage and creep. The former is caused by transfer of water from the concrete into the environment that leads to a reduction in volume, while the latter describes a strain increase caused by visco-elastic deformation of the calcium silicate hydrates in the hardened cement paste under a sustained stress. It has been reported that the increasing use of recycled coarse aggregates in RAC increases the rate of drying shrinkage of RAC (Gómez-Soberón, 2002; Matias et al., 2014; Tam and Tam, 2007; Thiery et al., 2013). This happens because of an increase in the paste volume (i.e. old adhered mortar and new paste) in RAC compared to NAC for a given strength class. As far as the creep is concerned, it increases with an increase in the RA content (Kou and Poon, 2008; Kou and Poon, 2012; Tam and Tam, 2007).

Permeability

Permeability is the ability of the concrete to permit flow of materials such as water, air (oxygen, carbon dioxide) and chlorides through the pore structure of the concrete. Low permeability is strongly correlated with good durability. The majority of researchers report that permeability of the RAC made with fully and/or partial replacement of NA by RA, is higher than that of NAC, mostly due to the higher amount of porosity and cracks existing in the adhered mortar, and/or the increased water-binder ratio that may be required to preserve workability. Water permeability increases with the substitution level of RAs, w/c ratio and age due to an increase in the volume of the interfacial transition zone between the cement paste and the aggregate (Bravo and de Brito, 2012; Thomas et al., 2013; Villagrán-Zaccardi et al., 2008). Permeability of concrete is greatly reduced when using e.g. fly ash or bagasse as partial replacement of cement; in some cases, the effect was observed to be more significant than that for NAC (Mousa et al., 2015; Somna et al., 2012).

Chloride penetration

Chloride penetration refers to the depth to which chloride ions can penetrate into concrete over a given time scale. The transport mechanism of chloride ions is rather complex and involves water diffusion, impregnation and capillary absorption (Matias et al., 2014).

Several studies have shown that it depends on factors like the NA replacement (Ann et al., 2009; Kou and Poon, 2012; Lotfy and Al-Fayez, 2015; Sim and Park, 2011; Villagrán-Zaccardi et al., 2008), w/c ratio (Lotfy and Al-Fayez, 2015; Vázquez et al., 2014; Villagrán-Zaccardi et al., 2008) and curing period (Bravo and de Brito, 2012). Chloride penetration increases in RAC with the increase in NA replacement owing to the increased permeability (see above). The addition of lime as a chemical admixture could potentially favour the chloride penetration, whereas the use of fly ash reduces it. As the fly ash content increases, the chloride penetration decreases (Kou and Poon, 2013; Lotfy and Al-Fayez, 2015; Sim and Park, 2011; Somna et al., 2012). The use of super plasticizers have exhibited positive results on the prevention of chloride penetration (as they allow lower water-binder ratios to be achieved). The addition of pulverized fuel ash and ground blast furnace slag appears to increase the chloride resistance (Tam and Tam, 2008), probably via similar mechanisms. In all cases though, the percentages of increase in chloride penetration of RAC compared to NAC were relatively small and could be compensated for easily by appropriate mix design.

Freeze and thaw resistance

Freeze and thaw resistance have been shown to greatly affect durability and strength of concrete. Literature review suggests that freeze and thaw resistance of RAC is poorer than that of NAC and it decreases with an increase in RA replacement ratio (Medina et al., 2013; Richardson et al., 2016; Tuyan et al., 2014). Reduction of adhered mortar content has been observed to increase the freeze thaw resistance of RAC, as does the addition of additives such as meta-kaolin (Gokce et al., 2004).

General conclusions on the use of RAs vs NAs

Based on the aforementioned results comparing the performance of a NAC to that of a RAC of the same strength class, (Corinaldesi and Moriconi, 2009; Corinaldesi and Moriconi, 2010; Sani et al., 2005) the RAC exhibits: a lower tensile strength (of approx. 10%), a lower elastic modulus (almost 20%), similar bond strength with the steel reinforcement, similar vulnerability to shrinkage cracking, equivalent durability characteristics in terms of resistance to freeze-thawing and unwanted penetration of various agents, and no leaching of any substances of concern (SoC) to the environment. These relatively minor differences could, if required, be easily corrected by adapting mix designs using normal methods (e.g. using super-plasticisers to reduce water-binder ratio and/or increase workability, increasing cement contents, or adapting coarse-fine aggregate ratios) or making minor adjustments to structural design parameters. This should encourage increased use of RAs as a replacement for NAs, to help achieve goals, technical regulations, guidelines and recommendations set by international organisations e.g. the EU (European Commission, 2010), that can be summarised in the following:

- limitation of C&D waste disposed to landfills;
- incentives for waste selection at source and implementation of 3R (reduce/reuse/recycle) strategy;
- development of recycled materials;
- inclusion of waste management as an integral part of building and demolition permit; and,
- incentives for use of recycled materials in public works.

SWOT analysis on C&D waste practices in the State of Qatar

Generic overview on C&D waste in Qatar and usefulness of SWOT analysis

Compared to other countries worldwide (Coelho and de Brito, 2013b; Kumbhar et al., 2013; Lu and Yuan, 2010; Rodríguez et al., 2015), the practices of C&D waste management in the State of Qatar are rather limited and still at an infant stage; this merely reflects the fact that the use of RAs has only been allowed in the QCS since 2014. Hence, there is a big knowledge and implementation gap in comparison to other regions globally. In addition, scientific literature on C&D waste techniques and methods (if any) implemented in Qatar is very limited. The present work aims at contributing to bridging this gap by providing useful insight into the current status of C&D waste management in Qatar with the use of a SWOT analysis.

SWOT analysis has been extensively used in literature for the analysis and effectiveness of a business or plan. In the waste management sector, SWOT analysis has been used to identify **S**trengths, **W**eaknesses, **O**pportunities and **T**hreats in various municipalities around the world (Pardo Martínez and Piña, 2017; Shahba et al., 2017; Yuan, 2013) either to discover the potentials and ways for initiating and successfully implementing an effective SWM program, or to prove the importance of implementing a viable and sustainable waste management sector, in order to resolve environmental concerns, regarding the pollution and protection of natural resources.

SWOT analysis on C&D waste management practices in Qatar

The SWOT analysis attempt performed is briefly depicted in Fig. 1 and further analysed in detail in the results and discussion section, below. The steps that were followed throughout the entire procedure were: a) collection and evaluation of data and information from relevant stakeholders, governmental entities (Public Work Authority and the Waste Treatment Centre in the Ministry of Municipality and Urban Planning), relative companies, construction industries, and individuals, b) classification of the collected information into the four SWOT factors, in order to complete the relative matrix and develop the relevant strategies. Strengths and weaknesses of the current C&D waste management practices in the State of Qatar were considered as “internal factors”, whereas threats and opportunities both locally as well as globally were considered as “external factors” (Halla, 2007; Kajanus et al., 2012). The matrix shown in Fig. 1 was also used to identify and formulate any potential strategies that would most possibly improve the current state of C&D waste customs and behaviours in Qatar.

STRENGTHS

S1. Economical and geographical location
S2. Future urban planning
S3. Future vision of the country
S4. Awareness of LAs

OPPORTUNITIES

O1. Urgent need and request for C&D waste management system
O2. Governmental and industrial support

SWOT
(Analysis of C&D waste management in the State of Qatar)

WEAKNESSES

W1. Absence of proper and strict regulations on C&D waste management
W2. Inappropriate or lack of in-situ (source) waste sorting
W3. Lack of a proper waste management infrastructure system
W4. No actual implementation of the “waste hierarchy” and 3R strategies

THREATS

T1. Landfills are limited and already burdened with other types of waste
T2. There is no landfill discharge fee applicable
T3. A local market for recycled C&D material is yet to be developed
T4. No substantial research in the area of C&D waste has actually been performed in the country so far

Fig. 1 SWOT analysis of C&D waste management in the State of Qatar.

Results and discussion

Strengths

Several factors have been identified as potential strengths that could lead to an improved and successful C&D waste management system in the State of Qatar. Some of these factors which are analysed in detail below are: geographical and economical location, future urban planning, future local vision, awareness from local authorities (LAs).

S1_Geographical and economical location: It is well-known worldwide that throughout the years Qatar has become one of the most economically developed countries of the Gulf Co-operation Council (GCC). This is a great achievement that the country can be based on to develop a proper, viable and sustainable future plan for the management of C&D waste. With existing availability in resources, the only thing that remains is the will to build an appropriate infrastructure and relative mechanisms that will see this plan through.

S2_Future urban planning: For years, Qatar has shown evidence of rapid development and growth in infrastructure, via the successful completion of mega structural projects and its direct quest and intention of being amongst the countries that seek the implementation of the concept of “smart cities”. Modern buildings, advanced and “green” transportation systems (new railway is about to be given in circulation within the year 2019), expressways roads, etc. are just a few examples of the country’s trajectory towards modern urbanization. However, it is common sense that all these activities create huge amounts of C&D waste, rendering their sound management imperative.

S3_Future vision of the country: The Qatar's National Vision (QNV2030) underlines an unequivocal commitment to maintaining harmony between the three inter-dependent pillars of sustainable development: economic growth, social development and environmental management. Managing, therefore, the waste in a sustainable manner is of utmost importance. In addition, Qatar has already demonstrated its commitment to achieving this objective by engaging in a number of waste related activities, for other streams of waste, such as DSWM, creating and involving into this the relative center (DSWMC).

S4_Awareness of LAs: Since 2010, the local government has been promoting programs and projects with the intention to minimize all waste streams throughout the country. However, it has been advocated in literature that individuals do tend to respond to waste management issues only when they perceive it as a threat to their own well-being. Training, therefore, these individuals about household waste management is one of the actions could further help to reduce waste and encourage recycling.

Weaknesses

The successful implementation of any sustainable and economically viable C&D waste management plan in the State of Qatar would require a set of regulations and legislations that cover all necessary steps for a proper treatment of C&D waste e.g. generation, collection, sorting, recovery, recycling and landfilling (as a last alternative). Nonetheless, the country is currently suffering from the lack of such regulations and, as such, the following weaknesses have been identified:

W1_Lack of regulations and legislations: Many of the stakeholders, industrial partners and individuals claimed that they are in need for proper legislations to follow and abide, while others expressed their concerns on the support and commitment of the LAs on that matter.

W2_*Non-existent or limited source separation of C&D waste*: The majority of our data sources indicated that for the time being there is no source separation of C&D waste, at the generation points (e.g. construction sites). What usually occurs is the transportation of mixed waste mostly to landfills.

W3_Lack of a waste management infrastructure system: Currently, the country lacks a proper, viable and integrated system for C&D waste with few transfer stations, processing, recovery and recycling facilities.

W4_No implementation of waste hierarchy and 3R strategies: There is a general lack of awareness from some decision makers and stakeholders on the multiple benefits gained when implementing waste hierarchy and the 3R strategies for C&D waste. A proper training of all these delegates should take place, incentivising also the public so as to practically contribute to any effort attempted on this part.

Opportunities

Out of the literature review performed for this research article and the correspondence we had with several stakeholders, governmental entities, companies, etc. we identified the following two opportunities:

O1_Urgent need for a waste management system: Due to the country's run up for the 2022 World Cup and to the rapid urbanization and development, there are a lot of mega structural projects currently going on, which they will continue for the years to come. It is, therefore, of utmost importance to put in place techniques, methods and strategies to create waste management infrastructure that can properly deal with C&D waste. Qatar can easily mobilize resources to that direction and support all efforts required for a successful implementation of that plan.

O2_Governmental and industrial support: From our correspondence, some stakeholders revealed that for a long period of time, C&D waste management problems have gained attention from the Qatari government, as well as from the related industry associations.

Threats

In the State of Qatar a number of threats were identified with regards to the proper management of C&D waste:

T1_Limited number of landfills already filled with other types of waste: Although the country has enough space that can be used for landfilling, statistics for 2014, 2015 and 2016 show that there was a huge generation of approx. 7.1, 9.3 and 9.7 million tonnes of C&D waste respectively, most of which (approx. 67%) ended up in open dumpsites. Naturally, some of these dumpsites have already been closed, whereas new ones were created, some of which are, in fact, controlled landfills.

T2_No applicable discharge fee: At the moment, there are no charges imposed for landfilling of C&D waste in the country. Therefore, contractors can freely deposit their waste.

T3_A local market for recycled C&D waste is yet to be developed: It is only since 2014 that QCS has allowed the use of recycled materials in the construction sector. Hence, the market for C&D recycled materials in Qatar is still under development. This fact provides limited or no incentives at all for stakeholders to venture and invest into C&D waste recycling projects.

T4_Lack of substantial research in the area of C&D waste: Compared to the EU or other regions globally, there has been relatively limited research on C&D waste management both in the State of Qatar, as well as in the Middle East. This fact creates no reference point, for the region, to initiate a viable and sustainable C&D waste management plan for the country.

Proposed strategies

The strategies (abbreviated below as: ***Str#***) proposed in this section were developed based on the principle of: "maximizing strengths and opportunities, overriding weaknesses through strengths, mitigating threats through strengths, and overriding weaknesses by avoiding threats". Based on the SWOT analysis depicted in Fig. 1, the proposed strategies were then classified in four categories, as shown in Fig 2.

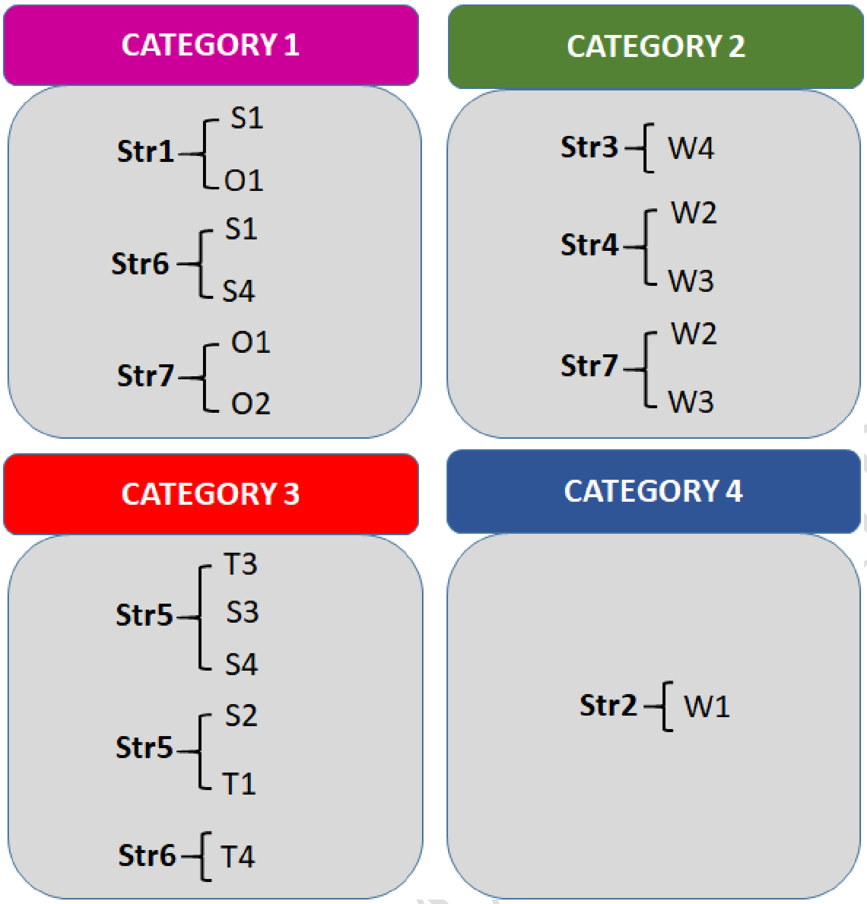

Fig. 2 Classification of C&D waste management proposed strategies (Str#), based on the SWOT analysis implemented, for the State of Qatar.

Str1: it is apparent that it is of utmost importance to clearly define C&D waste management plans in the country and engage all parties and entities involved so as to implement any potential mechanisms. Any specific responsibilities and roles should be clearly divided and assigned to the respective players. Combining the incentives that promote any reuse/recycle of C&D materials together with the provision of specialised education, skills and training could potentially transform the way this sector currently operates, creating at the same time opportunities for new business development (Iacovidou and Purnell, 2016).

Str2: there is, also, a need for establishing and broadcasting in all available media detailed regulations and directives relevant to C&D waste management practices in Qatar.

These should be supported by law enforcement and penalties for not abiding to them, to ensure adherence and compliance of all stakeholders involved.

Str3: furthermore, current reports and information available on C&D waste is rather vague and not properly documented. Thus, there is an inherent need to establish effective and reliable communication links among all stakeholders to avoid any discrepancies and ambiguities of data and information on C&D waste. Contractors and project planners should establish reliable means of recording the amounts of C&D waste generated from various projects in the State of Qatar. This can help in formulating any potentially effective waste management system and/or facility.

Str4: LCAs studies should be conducted to obtain a better view on the C&D waste management future plans.

Str5: promoting, establishing and developing a market of recycled C&D materials in Qatar should be a priority.

Str6: there is a need to create facilities, mechanisms and incentives for promoting interest in research on that sector.

Str7: finally, relative stakeholders should increase the awareness about C&D waste management through education, training and promotion campaigns. A truly successful implementation of any strategy and/or plan relies on the active engagement of all involved stakeholders, including the ordinary citizens.

As it can be seen from Fig. 2 the matching of the proposed strategies to the SWOT analysis can be done either uniquely (one-to-one) or in a multifaceted way (one-to-many).

Conclusions

The aim of this work is to provide insights into the benefits of using RAs as a replacement for NAs and to delineate the current state of C&D waste management practices in the State of Qatar via a SWOT analysis method.

Analysis of tests on RAC show that, if proper regard is taken to ensure that RAs are of suitable quality for concrete, the structural and durability properties of RAC are broadly comparable to those of NAC and any deficiencies could be easily rectified by relatively minor changes in mix design or structural detailing. This should encourage the greater use of RAs in concrete, reducing the social and environmental impact of the concrete fraction of C&D waste.

In addition, with regards to the State of Qatar, the results indicated that the country needs to maximize any strengths and opportunities in order to deal properly with the enormous amounts of C&D waste generated and formulate a viable and sustainable system for its proper management. The development and enforcement of clear directives, legislations and regulations is considered a necessity, so as to proactively address any issues associated with the generation and accumulation of C&D waste. Key issues in any proposed agenda or strategy should include: active involvement of all relevant stakeholders, increased awareness and enforcement of all legal formalities around C&D waste management and practices in Qatar, establishment of effective and reliable communication and coordination links among all players involved, an LCA implementation approach, and finally a market promotion of recycled construction materials in and out of Qatar, as well. The authors firmly believe that the proposed strategies could provide a starting point for local decision-makers to plan the development and implementation of a sound C&D waste management system in the country.

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