Journal of Advanced Concrete Technology

Materials, Structures and Environment

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Scientific paper

Sustainable Concrete made of Construction and Demolition Wastes using Recycled Wastewater in the UAE

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Received 8 June 2011, accepted 22 February 2012

doi:10.3151/jact.10.110

Abstract

Most of the previous research on the use of recycled materials for concrete examined only the effect of using recycled aggregate in concrete mixes. In this paper, the combined effects of recycled aggregate and recycled water on the strength and durability of recycled concrete are presented and discussed. Three types of mixing water were examined and found to comply with the requirements of EN 1008 and ASTM C94. The test program involved the preparation of a moderate strength concrete made out of recycled water and recycled aggregate obtained from demolition and construction wastes. In the demolition waste series, four mixes of concrete were prepared using different contents of aggregate extracted from demolition waste and recycled water. The effect of the recycled aggregate and recycled water on the axial and flexural strength was found to be moderate but had a significant negative impact on the durability. In the construction waste series, to enhance the durability and to lower the carbon footprint of the recycled concrete mix, the OPC was replaced by GGBS. Four replacement ratios, 60%, 70%, 80%, and 90%, of the OPC were examined. While all the four mixes achieved good strength and durability, the mix with 90% GGBS did not achieve the target strength of 40 MPa even after 56 days. In general, fully recycled concrete mix with 80% GGBS replacement is recommended for any sustainable future construction in the Gulf with an expected carbon footprint of 129.9 kg/m³.

1. Introduction

1.1 General

The construction industry annually consumes millions of metric tons of aggregate and fresh water around the world. Unsustainable consumption patterns of these materials have been identified as one of the key driving forces behind unsustainable development (Sakai 2010; Wilhelm 2010). A considerable portion of these materials goes to landfills as waste (Fisher and Werge 2009; EPA 2008, Dubai Municipality 2010). During the construction process, most of the waste comes from demolishing old concrete structures or from the concrete that exceeds the site's needs and the leftover on site or in the concrete trucks. The former type is termed herein Demolition Waste (DW) and the latter type is termed Construction Waste (CW). Statistics show that, globally, large amounts of materials are wasted annually. The Gulf Cooperation Council (GCC) countries rank in the top 10 of the world waste producers with 120 million tons of waste per year, and the figures are expected to reach 350 million tons by 2014 (Dubai Municipality 2010). Around 75% of this amount is construction and demolition wastes. The city of Dubai, in the UAE, alone

turns out more than 76,000 tons of waste every single day, the highest per capita worldwide (**Table 1a**). Unfortunately, most of this amount goes to landfills (**Fig. 1a**), posing risks to the local and regional environment. Making the consumption of these resources sustainable and mitigating the waste's environmental impact has been a long-standing objective of governments worldwide. Use of recycled materials (aggregate/water) in the construction industry has been an alternative under investigation for a while (Fisher and Werge 2009; EPA 2008; Dubai Municipality 2010).

A considerable amount of research is directed now towards how to reuse Recycled Aggregate (RA) and Recycled Water (RW) in making a sustainable concrete with a good performance in the long term and friendly to the environment. Engineers and scientists worldwide have been persistently researching and testing the feasibility of reusing the large amount of materials contained in construction and demolition wastes. Various reasonable solutions and alternatives have been researched. One of such alternatives is *fully* recycled concrete i.e. concrete totally made of RA and RW, which is the sub-

Table 1(a) Waste production (Fisher and Werge 2009, EPA 2008, Dubai Municipality 2010).

Region	EU-28	USA	GCC
Population in 2010 (million)	501	310	40
Total Waste (million ton/year)	2742	380	120
C&D Waste (million ton/year)	850	130	90
C&D Waste (ton/capita/year)	1.70	0.42	2.25
C&D Waste / Total Waste (%)	31%	35%	75%

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(a) Input material from landfill

(b) Output material

Fig. 1 Recycling of demolition waste in Dubai, UAE.

ject of this paper.

In recent years, there has been a growing research interest in concrete recycling because it offers a good resource of aggregate for new concrete and helps save natural resources and eliminate the need for disposal. Aggregate has been recycled from CW/DW at a reasonable quality and different grades and widely used in the construction industry as backfilling materials or sub-grade for roads. Further investigations were conducted to study the feasibility of using recycled concrete (RC) in the construction industry. Past examination of the basic properties of RA found RA to have lower bulk density, lower specific gravity, and higher water absorption compared to any natural aggregate (Dhir *et al.* 1998). Such higher water absorption greatly affects the workability of concrete and its strength as the water available for the hydration of cement is absorbed by the recycled aggregate (Li 2008). An international conference was fully devoted to the properties of concrete mixes made of recycled aggregate (Dhir *et al.* 1998) and more recently a number of research papers were written on the subject (Li 2008; Tsujino *et al.* 2007; Park *et al.* 2009; Grdic *et al.* 2009). However, few papers have focused on using recycled wastewater (Sales and De Souza 2009; Su *et al.* 2002; Chatveera *et al.* 2006).

The main objective of this paper is to examine the key mechanical properties of recycled model columns and beams by evaluating their strength and durability. Also, producing green concrete with a low carbon footprint was among the aims of this research. It is well known that the production of one ton of OPC produces a carbon footprint of about 1000 kg (Malhotra and Mehta 2008). One solution to reduce unacceptably high construction emissions is to replace the OPC in the concrete mix. Ground Granulated Blast furnace Slag (GGBS) is widely used to replace the cement to enhance the durability (Mehta 1984; Hooton 2000). GGBS is a by-product of the steel production process (thus it is a green

material), and it is used here to enhance the durability and lower the carbon footprint. Thus except for the remaining small quantity of OPC, the concrete used in the CW test series could almost be termed fully recycled concrete or in other words, 'green concrete'.

1.2 Mixing water specifications

Wastewater is treated and reused for beneficial purposes such as agricultural and landscape irrigation, industrial processes, toilet flushing, and replenishing ground water basins (referred to as ground water recharge). In addition to provide a dependable, locally controlled water supply, water recycling provides tremendous environmental benefits. By providing an additional source of water, water recycling can decrease the diversion of water from sensitive ecosystems. Other benefits include decreasing wastewater discharges and reducing and preventing pollution. While use of recycled water for non-drinking purposes is generally an accepted practice, public misperceptions and concerns still exist about its use. However, it can actually be a cheaper alternative compared to the cost of using drinking water. The cost of water recycling systems varies widely depending on the use and the level of treatment required (Judd 2011; Hammer and Hammer 2003).

This paper aims to investigate the possibility of using recycled wastewater from different sources as a mixing water for concrete. The quality of mixing water is critical to the properties of fresh and hardened concrete, including strength and durability. Most standards around the world specify that water used for concrete shall be free of oil, acid, alkalis, organic matter or other deleterious substances. Drinking water is largely used as the mixing water for concrete. However, as discussed above, drinking water resources are becoming more and more scarce in developed countries and are quite expensive in developing countries (Su *et al.* 2002; Chatveera *et al.* 2006). Thus three types of water are examined in this

Table 1(b) Chemical analysis of mixing water.

Parameter	Tap Water	MBR Water	WRP Water	EN 1008 (2002)	ASTM C94 (1994)
Chloride ion, ppm	71	92	85	< 1,000	< 1,000
Sulfate ion, ppm	19	46	32	< 2,000	< 3,000
PH	6.5	7.09	12.1	> 4	-
Total Suspended Solids (TSS), ppm	5	5	36	< 100	< 50,000
Total Dissolved Solids (TDS), ppm	234	328	1,826	< 2,000*	
Biochemical Oxygen Demand (BOD), ppm	10	2	26	-	-
Chemical Oxygen Demand (COD), ppm	40	16	200	-	-
Ammonia Nitrogen NH ₃ -N, ppm	1.2	0.11	-	-	-
Total hardness, (CaCO ₃), ppm	-	102	-	< 1,000	-
Oil and Grease, ppm	-	5	8	-	-

paper and their chemical analyses are shown in **Table 1(b)**. The first type is fresh tap water, which was used in the control mix and in the curing of all the specimens, even those that were made with recycled water. The second type is sewage water recycled using the Membrane Bioreactor (MBR) process, which was used to prepare the specimens in the demolition waste series (Judd 2011). It is worth noting that the cost of one cubic meter produced using the MBR process is about half of the cost of desalinated water. It is also worth noting that around 90% of the water consumed in the UAE is produced by desalination plants (Dubai Municipality 2010). The third type is water used in the washout operations (Su *et al.* 2002) in ready-mix concrete plants, recycled using the Wet Recycling Process (WPR). Such water was used to prepare the specimens in the construction waste series. It is worth noting that raw sewage water is not allowed for use in concrete mixing according to EN 1008 (2002) and ASTM C 94 (1994). These specifications allow non-potable water to be qualified by chemical and strength testing. The chemical analysis comparison presented in **Table 1(b)** shows that the three types of water are qualified according to EN 1008 (2002) and ASTM C 94 (1994). The hardened concrete strength results for the three types of water are presented in Section 3 of this paper.

2. Test program

2.1 Demolition waste Recycled aggregate materials

The recycled aggregate was obtained from a recycling plant for demolition waste in the UAE, where concrete blocks are segregated into different categories and crushed into aggregate to be primarily used for the construction of roads. The average measured density and water absorption of the recycled aggregate were 2.51 t/m³ and 5.2%, respectively. Thus it may be classified as Low quality (L) according to Japanese Standards (Tsujino *et al.* 2007). The aggregates were then sieved to separate the 10 mm and 20 mm size particles for use in the concrete mixes being tested (see **Fig. 1**). Except for

cleaning, no further treatment was performed on the RA (e.g. the surface modification treatment in Tsujino *et al.* 2007) after it was obtained from the plant. The recycled aggregates were not saturated with water prior to the mixing operation.

MBR recycled water

The amount of recycled water that was used to make the concrete mixes was obtained from a compacted wastewater treatment plant recently constructed in Dubai. The water was treated using the Membrane Bioreactor (MBR) technique, which recycles sewage into water of a relatively high quality to make it reusable (**Table 1b**). The MBR technique, shown in **Fig. 2**, is a process that combines a membrane filtration process and an acti-

Fig. 2 MBR system for wastewater treatment.

Table 1(c) Chemical analysis of cementitious material.

PC - CEM I 42.5N BS EN 197 (2000)	Constituent/property (%)								
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Mn ₂ O ₃	SO ₃	S	Cl
	21.29	4.89	3.42	64.16	1.41	----	2.53		0.010
GGBS - BS 6699 (1992)	33.22	16.12	0.72	42.42	5.53	0.30	0.32	1.30	0.009

Table 2(a) Recycled water (RW) series test results.

Recycled Water (RW) Series							
General Details	Trial Mix#		1	2	3	4	5
	Recycled Material (%)		0%	25%	50%	75%	100%
	Grade	N	40	40	40	40	40
	Cement	kG	370	370	370	370	370
	Water	kG	159	159	159	159	159
	GGBS	kG	-	-	-	-	-
	W/cm	--	0.43	0.43	0.43	0.43	0.43
	Admixture	g/m ³	5500	5500	5500	5500	5500
Cube Strength (7 Days)	#1	MPa	51.0	50.6	47.9	46.6	48.4
	#2	MPa	47.0	47.7	45.8	47.0	46.1
	#3	MPa	51.7	48.8	49.2	43.0	49.5
	Average	MPa	49.9	49.0	47.6	45.5	48.0
Cylinder Strength (28 Days)	#1	MPa	54.4	55.2	55.8	57.7	54.4
	#2	MPa	40.1*	55.2	57.0	53.0	51.7
	Average	MPa	54.4	55.2	56.4	55.4	53.1
Bending Strength (28 Days)	Plain	kN.m	2.25	2.81	2.48	1.91	2.36
	Top	kN.m	4.61	3.38	3.49	3.83	3.26
	Bottom	kN.m	6.41	7.88	7.31	8.33	6.41
	Top & Bot	kN.m	9.79	8.44	7.31	8.44	8.21
Durability Average (28 Days)	RCP	Coulombs	5215	5912	6206	6637	6941
	WP	mm	18	24	27	30	33
	WA	%	2.9	3.6	4.2	4.6	4.8
	ISAT	ml/m ² /sec	0.05	0.07	0.08	0.09	0.11

*The cylinder was tested without a cap, thus it was disregarded in the determination of the average value

vated sludge process (Judd 2011; Hi Star Water Solution 2010). The MBR process is used in place of the secondary sedimentation tank where a sand filter is often used for tertiary treatment in the conventional activated sludge process. By adopting a simple and high-performance flat sheet type membrane of 0.1 µm pore size, the MBR system effectively provides space saving and ease of maintenance and operation. In addition, the removal of nitrogen and phosphorus can be achieved by anoxic/oxic advanced treatment. The measured chlorides and sulfates contents in the effluent of the MBR process were 92 and 46 ppm, respectively. These values are significantly lower than the allowable limits in EN 1008 (2002) for mixing water used in reinforced concrete of 1000 and 2000 ppm, respectively (**Table 1b**). Tap water was used for the control mix where the measured chlorides and sulfates contents were 71 and 19 ppm, respectively.

DW specimens

A total of 27 standard cubes measuring 150x150x150

mm and 18 standard cylinders 150 mm in diameter and 300 mm long were prepared to BS 1881-116 (1983) and 40 beams measuring 750x150x150 mm to BS 1881-118 (1983). The control mix was composed of 370 kg OPC, 159 kg of tap water, 559 kg of 20 mm crushed RAK Rock, 365 kg of 10 mm crushed RAK Rock, 699 kg of 5 mm crushed RAK Rock and 238 kg of dune sand. **Table 1(c)** lists the chemical analysis of the cementitious material used in this project. One commercial chemical super-plasticizer was used in all the mixes with 5500 g/m³. **Table 2(a)** and **(b)** provide details for the test specimens. Only the 10 mm and 20 mm aggregate particles were replaced by recycled aggregate after it was sieved. The percentage by weight of the recycled water and recycled aggregate were 0%, 25%, 50%, 75% and 100%. The term "RW" refers to concrete made using Recycled Water only, whereas the term "RWRA" was used to define concrete made using both Recycled Water and Recycled Aggregate. Four different types of beam reinforcement were examined, Plain, Top, Bottom and Top+Bottom (T&B). All the longitudinal reinforcements

Table 2(b) Recycled water recycled aggregate (RWRA) series test results.

Recycled Water Recycled Aggregate (RWRA) Series							
General Details	Trial Mix #		1	6	7	8	9
	Recycled Material (%)		0%	25%	50%	75%	100%
	Grade	N	40	40	40	40	40
	Cement	kG	370	370	370	370	370
	Water	kG	159	159	159	159	159
	GGBS	kG	-	-	-	-	-
	W/cm	--	0.43	0.43	0.43	0.43	0.43
Cube Strength (7Days)	Admixture	g/m ³	5500	5500	5500	5500	5500
	#1	MPa	51.0	42.3	42.2	38.6	36.2
	#2	MPa	47.0	43.3	43.2	37.9	34.3
	#3	MPa	51.7	42.2	43.6	38.4	33.9
	Average	MPa	49.9	42.6	43.0	38.3	34.8
Cylinder Strength (28 Days)	#1	MPa	54.4	44.5	46.8	41.0	36.5
	#2	MPa	40.1*	46.9	47.1	42.4	40.5
	Average	MPa	54.4	45.7	47.0	41.7	38.5
Bending Strength (28 Days)	Plain	kN.m	2.25	2.36	2.36	2.14	2.14
	Top	kN.m	4.61	3.94	4.05	4.05	3.38
	Bottom	kN.m	6.41	8.44	8.78	8.44	5.74
	Top&Bot	kN.m	9.79	8.44	9.56	7.31	8.10
Durability Average (28 Days)	RCP	Coulombs	5215	7057	7411	7810	8436
	WP	mm	18	39	43	47	53
	WA	%	2.9	5.0	5.2	5.4	5.9
	ISAT	ml/m ² /sec	0.05	0.11	0.13	0.14	0.16

* The cylinder was tested without a cap, thus it was disregarded in the determination of the average value

were 2T10 bars. No stirrups in the first 3 types were used, but the last type with T&B reinforcement had 9T10 stirrups. Note the letter “T” refers to the high tensile steel according to Eurocode 2 (1992) with 500 MPa yield strength. After mixing, molding and demolding, two different curing procedures were applied at room temperature up to the day of testing. The cubes and cylinders were immersed in a fresh tap water tank, whereas each concrete beam was wrapped in a plastic sheet.

2.2 Construction waste

Recycled aggregate materials

In this project, aggregate obtained from recycled CW was used, in particular aggregate recycled from concrete wasted in concrete mixing plants and trucks. The aggregate here was recycled by the so-called Wet Recycling Process (WRP), which is used in a number of ready mix plants around the world (Su *et al.* 2002; Jungmann and Quindt 1999; Handycrte 2011; Elchalakani and Elgaali 2010). The wet recycling plant consists of two main parts: a concrete reclaimer and an automated water treatment system, as shown in Fig. 3. The concrete reclaimer is used to separate aggregate of different sizes from the other materials in the concrete mix. The automated water treatment mechanism is provided with an agitator, and flocculants are added to the process water to wash out the cement and other material of the cement paste in order to separate the water. The plant is pow-

ered with green energy (electricity) and the production of the recycled aggregate is fairly simple. First, a truck carrying remaining concrete drives in from a site and the driver unloads its content at the plant. Through a series of sieves, the aggregates are divided into coarse and fine grades in two separate areas. A standard oven is used to remove the moisture from the aggregate. Then, a standard sieve is used to separate the aggregate into

Fig. 3 The wet recycling plant (Elchalakani and Elgaali 2010).

different sizes of 5 mm, 10 mm, and 20 mm. The average measured density, specific gravity, and water absorption of the recycled aggregate were 2.645 t/m^3 , 2.66, and 1.03%, respectively. Thus it may be classified as Middle to High quality (M to H) according to Japanese Standards (Tsujino *et al.* 2007).

WRP recycled water

The recycled water that was used in the concrete mixes in this part of the research was obtained from the wet recycling process itself. After it is used to wash the aggregate, the water is directed to a small-scale water treatment plant within the ready mix plant to recycle it and at the same time reduce its chloride content. In general, the quality of the recycled water obtained from WRP was much better than the quality of the material obtained from demolition waste using the MBR process. Chlorides and sulfates are specifically reduced in the recycled water to minimize the risk of concrete deterioration and fracture in the future. The measured chlorides and sulfates contents in the effluent of the WRP process were 85 and 32 ppm, respectively. These values are lower than the values obtained from MBR treatment (Table 1b) and significantly lower than the allowable limits in EN 1008 (2002) for mixing water used in reinforced concrete of 1000 and 2000 ppm, respectively. Thus, the quality of the mixing water used in the demolition waste test series was lower than that used in the construction waste, which was reflected on the scatter found in the test results presented in Section 3.1.

CW specimens

The test program involved the preparation of a moderate strength concrete C40 (nominal strength 40 MPa) out of recycled water and recycled aggregate. A total of 72 standard cubes measuring 150x150x150 mm were prepared and tested according to BS 1881-116 (1983). The quality of the recycled aggregate obtained from the construction waste exceeded of the aggregate obtained from the demolition waste. The aggregate produced by the WRP has less dust and slime contamination, is better

separated, better classified and particularly free from organic matter (Jungmann and Quindt 1999). This made the results more consistent with less irregularity and scatter.

In general, the concrete specimens made using the RW from the WRP treatment achieved strength very similar to the cubes made using the tap water and in certain replacement percentages they even provided slightly higher strength, particularly at an early age. The alkaline nature of such water where the amount of solids is significantly higher than the tap water (TDS=1826, PH=12.1 in Table 1b) would not only accelerate the cement hydration but also activate the pozzolanic reaction of the mineral admixture, i.e., the GGBS. Thus, the case of 100% RW is not presented in this paper as the quality of the effluent from the wet recycling process was good and it had negligible effect on the strength and durability of the recycled concrete. Therefore, only the 100% RA and the 100% RWRA are examined and presented in this paper.

Four recycled concrete mixes were tested in the construction waste series. In the four mixes, the OPC was replaced by different amount of GGBS, namely, 60% (G60), 70% (G70), 80% (G80) and 90% (G90). The details of these mixes are given in Tables 3 to 7. The characteristics of the trial mixes were compared to a baseline (control) mix proposed for Masdar City, a future environmentally friendly city with almost zero carbon foot-print in the UAE. One commercial chemical super-plasticizer was used in all the mixes with a concentration of 4500 g/m^3 . All the proposed mixes had a carbon footprint less than the baseline mix except G60, and the G80 and G90 mixes had the lowest carbon foot-prints, of 129.9 and 100.2 kg/m^3 , respectively. The four mixes were made once using 100% RA and in the other using 100% RA+100% RW.

Four tests were performed to measure the durability of the recycled concrete: the Rapid Chloride Penetration (RCP) test according to ASTM C1202-97 (1997), the Water Penetration (WP) test according to both DIN 1048 (1991) and BS EN 12390-8 (2000), the Water Ab-

Table 3 Characteristics of control mix with 0% recycled material and 0% GGBS.

	Control Mix (0% GGBS)					
	Material	Source	CO ₂ kg/Ton	Cost/Ton	Mat kg/m ³	CO ₂ kg /m ³
Binder	OPC	UAE	959	240	148	141.932
	GGBS	UAE	155	280	222	34.41
	Fly Ash	India	93	300	0	0
Total Binder					370	
	Water	UAE	1	25	138	0.138
	W/C				0.37	
Aggregates	20 mm Aggregate	RAK	7	48.5	700	4.9
	10 mm Aggregate	RAK	7	48.5	340	2.38
	5 mm Aggregate	RAK	7	51	540	3.78
	Dune Sand	AL Ain	5	25	380	1.9
Total Aggregates					1960	0
Admixture ltr/m ³			508	5	4.5	2.286
Total CO ₂ kg/m ³						191.726

Table 4 Characteristics of concrete mix with 40% OPC and 60% GGBS.

	60% GGBS					
	Material	Source	CO ₂ kg/Ton	Cost/Ton	Mat kg /m ³	CO ₂ kg /m ³
Binder	OPC	UAE	959	240	148	141.932
	GGBS	UAE	155	280	222	34.41
	Fly Ash	India	93	300		0
Total Binder					370	
	Water	UAE	1	25	138	0.138
	W/C				0.37	
Aggregates	20 mm Aggregate	RAK	7	48.5	700	4.9
	10 mm Aggregate	RAK	7	48.5	340	2.38
	5 mm Aggregate	RAK	7	51	540	3.78
	Dune Sand	AL Ain	5	25	380	1.9
Total Aggregates					1960	0
Admixture ltr/m ³			0	0	0	0
Total CO ₂ kg/m ³						189.44

Table 5 Characteristics of concrete mix with 30% OPC and 70% GGBS.

	70% GGBS					
	Material	Source	CO ₂ kg/Ton	Cost/Ton	Mat kg /m ³	CO ₂ kg /m ³
Binder	OPC	UAE	959	240	111	106.449
	GGBS	UAE	155	280	259	40.145
	Fly Ash	India	93	300		0
Total Binder					370	
	Water	UAE	1	25	138	0.138
	W/C				0.37	
Aggregates	20 mm Aggregate	RAK	7	48.5	700	4.9
	10 mm Aggregate	RAK	7	48.5	340	2.38
	5 mm Aggregate	RAK	7	51	540	3.78
	Dune Sand	AL Ain	5	25	380	1.9
Total Aggregates					1960	0
Admixture ltr/m ³			0	0	0	0
Total CO ₂ kg/m ³						159.692

Table 6 Characteristics of concrete mix with 20% OPC and 80% GGBS.

	80% GGBS					
	Material	Source	CO ₂ kg/Ton	Cost/Ton	Mat kg /m ³	CO ₂ kg /m ³
Binder	OPC	UAE	959	240	74	70.966
	GGBS	UAE	155	280	296	45.88
	Fly Ash	India	93	300		0
Total Binder					370	
	Water	UAE	1	25	138	0.138
	W/C				0.37	
Aggregates	20 mm Aggregate	RAK	7	48.5	700	4.9
	10 mm Aggregate	RAK	7	48.5	340	2.38
	5 mm Aggregate	RAK	7	51	540	3.78
	Dune Sand	AL Ain	5	25	380	1.9
Total Aggregates					1960	0
Admixture ltr/m ³			0	0	0	0
Total CO ₂ kg/m ³						129.944

sorption (WA) test according to BS 1881-122 (1983), and the Initial Surface Absorption of concrete (ISAT) test according to BS 1881-208 (1996). In the Gulf, concrete accepted for the construction of high-rise buildings with about 50 years design life should have a good du-

rability with WA of less than 2.0%, RCP of less than 1000 Coulombs, ISAT of less than 0.05 ml/m²/sec, and WP of less than 10 mm. These later limits will be used to assess the durability test results presented in the following section.

Table 7 Characteristics of concrete mix with 10% OPC and 90% GGBS.

	90% GGBS					
	Material	Source	CO ₂ kg/Ton	Cost/Ton	Mat kg /m ³	CO ₂ kg /m ³
Binder	OPC	UAE	959	240	37	35.483
	GGBS	UAE	155	280	333	51.615
	Fly Ash	India	93	300		0
Total Binder					370	
Aggregates	Water	UAE	1	25	138	0.138
	W/C				0.37	
	20 mm Aggregate	RAK	7	48.5	700	4.9
	10 mm Aggregate	RAK	7	48.5	340	2.38
	5 mm Aggregate	RAK	7	51	540	3.78
	Dune Sand	AL Ain	5	25	380	1.9
	Total Aggregates				1960	0
Admixture ltr/m ³			0	0	0	0
Total CO ₂ kg/m ³						100.196

3. Test results

3.1 Demolition waste Concrete cubes

Table 2(a) and (b) list the test results for the test specimens. In general, the axial cube strength declines with increases in the amount of recycled material. **Figure 4** shows that the maximum reduction in the axial cube strength at 7 days is 30.3% for the cubes made with 100% RWRA. However, the maximum reduction in strength is only 8.8% for the cubes made with 75% RW. Similar trends were found at 28 days. Previous research showed that the axial compressive strength of concrete declines with increases in the amount of RA (Dhir *et al.* 1998; Li 2008; Park *et al.* 2009; Grdic *et al.* 2009). The research showed that when the RA is less than 20%, its influence is negligible; however when it reaches 100%, the reduction in strength is in the range of 12% to 25%. The researchers gave the following reasons for such reduction: (i) the RA has a relatively higher water absorption hence absorbs the water required for hydration of the cement, (ii) the RA is bounded by the old cement paste, which acts as a barrier between the RA and the new cement paste, and (iii) effect of curing time. Previ-

ous research (Alnaser 2008; Algaoud 2008) for concrete made of 75% RA has shown that increasing the curing time from 35 days to 45 days increased the cube compressive strength by 11.3%. The irregular effect of increasing the amount of RW or RWRA on the cube strength shown in **Fig. 4** is related to the low-quality aggregate and water used in the present test specimens. More research is needed in the future to examine the effect of RW and/or RA on the degree of hydration of cement (bond) of the recycled concrete. Previous tests (Malesev *et al.* 2010) using low-quality RA showed similar scatter in the compressive and bending strength results. Also, significant scatter was found in Sales and De Souza's (2009) test results for treated sewage sludge. To eliminate the scatter found in the present tests, the aggregate should be subjected to further treatment such as mechanical scrubbing to remove the cement paste (Tsujino *et al.* 2007) and the water can be treated further using the reverse osmosis process (Judd 2011).

EN 1008 (2002) specifies that the maximum reduction in the cube strength at 7 days shall not be more than 10% for the accepted water that is qualified by using chemical and strength tests. **Figure 4** shows that the maximum reduction in the cube strength when using the MBR recycled water is 8.8% at 7 days. **Table 1(b)** shows that the measured mineral contents of the MBR treated water are generally less than those specified in EN 1008 (2002). Thus the MBR treated water may be qualified according to EN 1008 (2002).

Concrete cylinders

It is seen in **Fig. 5** that the maximum reduction in the 28 days strength is 29.2% for the cylinders made with 100% RWRA. However, the maximum reduction in the 28 days strength is only 14.0% for the cylinders made with 100% RW. It can be concluded that the effect of increasing the quantity of the recycled water and recycled aggregate is more pronounced compared to only increasing the recycled water. Also the reduction in strength for the cylinders (at 28 days) with 100% RWRA is almost the same (29.3% versus 30.3%) for the

Fig. 4 Effect of %recycled material on axial cube strength at 7 days.

Fig. 5 Effect of % recycled material on axial cylinder strength at 28 days.

concrete cubes (at 7 days) even when they were tested at different ages. This may lead to the conclusion that the presence of the recycled materials (water and aggregate) significantly affects the bond of the recycled concrete. Past tests on recycled aggregate concrete (Li 2008) showed that the concrete cylinder strength is 82% of the cube, however for normal concrete this ratio is about 85% according to Eurocode 2 (1992) due to the confining effects of the cube.

Concrete beams

The results of the concrete beams are presented in Figs 6 to 9. A number of interrelated factors can affect the

Fig. 6 Effect of % recycled material on plain beam bending strength.

Fig. 7 Effect of % recycled material on beam bending strength with top reinforcement.

bending strength of the recycled concrete beams including but not limited to: (a) the steel-concrete interface bond strength; (b) the new cement paste-recycled aggregate interface bond strength; (c) the amount and quality of recycled aggregate; (d) the amount and quality of recycled water; (e) the presence and location of the steel reinforcement in the beam cross section, i.e. plain, top, bottom, or top and bottom; (f) the percentage of the steel reinforcement area to the concrete beam cross sectional area ($\%A_s/A_c$); (g) the presence and percentage of the stirrups cross sectional area relative to the beam cross sectional area ($\%A_{sv}/A_c$). Significant scatter (irregularity) in the test results is shown in Figs 6 to 9. It is believed that the main reason for such scatter is the quality of the recycled water and aggregate used. However, more research is needed to examine the effect of each of the above factors in isolation to gain insights into the reason for the irregularity.

The bending strength of the beam was significantly affected by the presence of the recycled water. Adding the RA to the RW had a comparatively small effect on the bending strength.

It was found that both the plain beams and beams with top reinforcement failed in bending mode but the other two types with top and bottom reinforcement and beams with only bottom reinforcement failed in shear mode. In general, the bending strength of beams with reinforcement showed large scatter in the results, which

Fig. 8 Effect of % recycled material on beam strength with bottom reinforcement.

Fig. 9 Effect of % recycled material on beam strength with top and bottom reinforcement.

Fig. 10 Effect of % recycled material on durability by using RCP test.

Fig. 11 Effect of % recycled material on durability by using WP test.

reflects similar scatter in the relationship between the bond strength of the reinforcing bar and the %RA found in the tests presented in Li (2008).

It is seen in **Fig. 6** that the maximum reduction in strength is 15.0% for the plain beams made with 75% RW. However, the maximum reduction in strength is only 5.0% for the plain beams made with 100% RWRA. **Figure 7** shows that the maximum reduction in strength was 29.3% for the beams with top reinforcement made with 100% RW. However, the maximum reduction in strength is only 36.6% for the beams made with 75% RWRA. It is seen in **Fig. 8** that there is no reduction in strength for the beams with bottom reinforcement made with up to 100% RW. However, the maximum reduction in strength is only 10.5% for the beams made with 100% RWRA. **Figure 9** shows that there is 25.3% reduction in strength for the beams with T&B reinforcement made with up to 50% RW. However, the maximum reduction in strength is 25.3% for the beams made with 75% RWRA. It can be noted that the beams with bottom reinforcement had the most severe reduction of 29% for RW and 36% for RWRA.

Durability test results

The results presented in **Figs 10 to 13** show that the durability represented by the key four measures (RCP, WA, WP, ISAT) deteriorated proportionally with increases in the amount of RW and RWRA. In the following, the reasons for such deterioration are discussed. It is well known that concrete porosity is the prime factor

Fig. 12 Effect of % recycled material on durability by using WA test.

Fig. 13 Effect of % recycled material on durability by using ISAT test.

that affects the durability of concrete (Neville 1995; Collepardi 2006; Mehta and Monteiro 2006) and a key measure for it is the water absorption of concrete. The water absorption of the recycled concrete depends on the quantity of the recycled material as shown in **Fig. 12**. The amount of absorbed water proportionally increases with increases in the recycled material (aggregate and water) content. Water absorption depends on the porosity of the cement matrix of the recycled concrete (Malesev *et al.* 2010), for example, if the recycled aggregate is produced from low porosity waste concrete, and water absorption of the new concrete depends on the achieved structure of the new cement matrix. The recycled aggregate was found to have considerably high water absorption of 5.2% where such new structure was more porous and hence achieved very low durability with high WA, WP, and ISAT values (**Table 2a, b**). The other factor affecting the water absorption is the presence of the recycled water, which appeared to have chemically affected the degree of hydration of the cement matrix, also leading to a new porous structure. Neville (1995) showed that the porosity of concrete is significantly affected by the degree of hydration.

The amount of chloride ion penetration was significantly large in the RCP test (**Fig. 10, Table 2**) because of: (i) the porous structure of the recycled concrete resulting from both the high water absorption of the recycled aggregate and the lesser degree of hydration of the cement due to the presence of the recycled wastewater; and (ii) the comparatively higher chloride ion content

found in the MBR recycled wastewater used in the mix (**Table 1b**).

It is seen in **Fig. 10** that the maximum increase in coulombs is 29.3% for the cubes made with 100% RW. However, the maximum increase in coulombs is 61.8% for the cubes made with 100% RWRA. **Figure 11** shows that the maximum increase in the water penetration (WP) is 83% for the cubes made with 100% RW. However, the maximum increase in WP is 194.4% for the cubes made with 100% RWRA. **Figure 12** shows that the maximum increase in water absorption (WA) is 65.5% for the cubes made with 100% RW. However, the maximum increase in WA is 103.5% for the cubes made with 100% RWRA. **Figure 13** shows that the maximum increase in initial surface water absorption testing (ISAT) of recycled concrete is 120% for the cubes made with 100% RW. However, the maximum increase in ISAT is 220% for the cubes made with 100% RWRA.

The above results consistently showed that the maximum deterioration in durability was for the 100% recycling which was applicable for both RW and RWRA, where the deterioration for RWRA was almost double that for RW. The current tests used OPC, thus to enhance the durability of recycled concrete, fly ash and/or GGBS must be used for any future building construction in the Gulf to obtain high durability. However, for pavement construction or industrial floors, OPC may be adequate.

3.2 Construction waste

Strength results

A summary of the concrete trial mix results made of recycled aggregate (RA) and RWRA are shown in **Tables 8 and 9**, respectively. **Figure 14** shows the plots of these results. **Figs 15 and 16** show the cube axial strength measured at 7 days and 28 days for G70 and G80, respectively. The mix G00-N is the control mix since it does not contain any GGBS nor any recycled material. The mixes G70-N and G80-N do not have any recycled material but have 70% and 80% GGBS, respectively. The mixes G70-RA and G80-RA both have 100% recycled aggregate. The mixes G70-RWRA and G80-RWRA both have 100% recycled aggregate and 100% recycled water. It is seen that the reduction in strength is significantly affected by the amount of the GGBS and the presence of the recycled water and recycled aggregate.

In comparison with the control mix, the mixes G70-N and G80-N had reductions in strength at 7 days of 11.9% and 23.97%, respectively. In comparison with the control mix, the mixes G70-N and G80-N had reductions in strength at 28 days of 8.42% and 17.58%, respectively. Thus, the reduction in strength depends on the quantity of the GGBS and it is more pronounced at an early age due to the slower degree of hydration often found with GGBS blended cement.

In comparison with the control mix, the mixes G70-RA and G80-RA had reductions in strength at 7 days of

48.73% and 54.44%, respectively, and reductions of 38.97% and 43.03%, at 28 days. These reductions in strength were due to both the presence of the GGBS and the RA. In comparison with the G70-N, the G70-RA had reductions in strength at 7 days and 28 days of 41.8% and 38.97% (**Table 10**), respectively. These later reductions in strength were purely due to the presence of the RA only. Also, in comparison with the G80-N, the G80-RA had reductions in strength at 7 days and 28 days of 40% and 30.88%, respectively. Similarly, these later reductions in strength were purely due to the presence of the RA but they were lower than the corresponding values for the G70-RA, particularly at 28 days.

In comparison with the control mix, G70-RWRA had reductions in strength at 7 days and 28 days of 53.49% and 41.41%, respectively. Also, the G80-RWRA had reductions in strength at 7 days and 28 days of 57.62% and 48.15%, respectively. In comparison with the G70-N, the G70-RWRA had reductions in strength at 7 days and 28 days of 47.2% and 36.03%, respectively. In comparison with the G80-N, the G80-RWRA had reductions in strength at 7 days and 28 days of 44.26% and 37.1%, respectively. These later reductions in strength were purely due to the presence of the RA and RW but they are lower than the corresponding values for the G70-RWRA, particularly at 7 days. It may be concluded that increasing the amount of the GGBS in recycled concrete mixes containing RW and/or RA from construction waste has beneficial effects on the strength at early and old ages.

The reduction in strength due to only the presence of the recycled water from the WRP process can be theoretically determined from the above results (i.e. RW=RWRA-RA). The reduction in the cube strength for G70 at 7 days due to the presence of the recycled water only is predicted as 5.4% ($47.2-41.8=5.4$). The reduction in the cube strength for G80 at 7 days due to the presence of the recycled water only is predicted as 4.26% ($44.26-40=5.4$). These later values (5.4% and 4.26%) are lower than the allowable 10% reduction permitted in EN 1008 (2002) and ASTM C 94 (1994) to qualify non-potable water. Also, they are lower than the 8.8% reduction in strength obtained from the MBR process (**Table 10**). It is seen in **Table 10** that adding the RW to the RA in the CW series improved (indicated by positive sign) the durability unlike for the case of the DW series where the durability significantly deteriorated. This may have resulted from the RW produced by the WRP being more alkaline as it contains a large amount of solids, mostly cement and other particles (TDS=1826 and PH=12.1).

Durability results

The durability limits were noted in Section 2.2 for concrete buildings in the Gulf. For the RA series, only G80 and G90 achieved low WA, RCP, ISAT and WP values of 1.13%, 670 Coulombs, 0.012 ml/m²/sec, and 9 mm, respectively, and thus they were considered suitable for

Fig.14 CW Series: strength and durability results for RA and RWRA mixes.

construction in the Gulf (see Table 8 and Fig. 14). However, it is seen that although the G90 had such good durability results it could not achieve the target 40 MPa bench mark even after 56 days. Thus the G90 cannot be recommended for the construction in the Gulf. In comparison, the G80 at 28 and 56 days had cube strength of 42.3 and 45.2 MPa, respectively.

For the RWRA series, only the G80 and G90 mixes, particularly G90, achieved favorably low WA, RCP, ISAT and WP values of 1.21%, 413 Coulombs, 0.012 ml/m²/sec, and 8 mm, respectively, and thus they were considered suitable for construction in the Gulf (see Table 9 and Fig. 14). However, even though G90 had such good durability results, it could not achieve the target 40 MPa benchmark even after 56 days. Thus G90 cannot be recommended for construction in the Gulf. In comparison, G80 at 28 and 56 days had strength of 38.5 and 45 MPa, respectively.

Figures 17 and 18 show the WA and the RCP values for the G70 and G80 mixes, respectively. It is seen that the best performance was for the mixes containing GGBS but without any recycled material, i.e., G70-N and G80-N, particularly the later. It may be concluded that increasing the amount of GGBS in the recycled concrete mixes containing RW and/or RA from construction waste has beneficial effects on durability. Figure 19 shows selected photos from the project performed at Dubai Men's College.

4. Conclusions

The results show that the mechanical properties of the recycled concrete made of recycled aggregate and recycled wastewater depend above all on the quality of the recycled material rather than its quantity. In general, the quality of the recycled material obtained from the construction waste was found to be better than the quality of the material obtained from the demolition waste. This made the results more consistent and reduced the irregularity. It was found that the MBR recycled water and the WRP recycled water both can be qualified to EN 1008 (2002) and ASTM C 94 (1994) based on chemical and strength tests.

With regard to concrete made of demolition waste, it was found that the effect of recycled aggregate and water on axial and bending strength was moderate, less than 40% deterioration, but had a significant effect on durability, where the deterioration was on the order of 200%. The durability tests consistently showed that the maximum deterioration is for 100% recycling, which was applicable for both RW and RWRA, where the deterioration for RWRA was almost double that for RW. The effect of increasing the amount of both RW and RA on the axial strength of cubes and cylinders is more pronounced compared to RW only. Also the maximum reduction in strength for cylinders with RW was larger than the case of concrete cubes made with RW. It was also found that the beams with bottom reinforcement

Table 8 Construction Waste- Recycled aggregate (RA) test results.

Recycled Aggregate Strength and Durability Results							COMPRESSIVE STRENGTH OF CUBES, N/mm ²			DURABILITY RESULTS				MIXED REMARKS
Date of casting	Ref. no.	Mix Code	Target Strength	w/c	Slump, 0 min	Slump, 30 min	7 days	28 days	56 days	WA, %	RCP, coulombs	ISAT, ml/m ² /sec	WP, mm	
										BS1881:122:89	ASTMC1202:97	BS1881:208:96	DIN 1048:1991 Part 5	RA only
18-Mar-10	LTM 550	G60	40	0.37	160	150	36.0	49.0	56.0	2.54	1294	0.068	23	(60%GGBS)-148-OPC+222-GGBS-370 Kg/m ³ - Binder
							37.0	49.0	55.0	2.53	1391	0.063	12	
							36.0	46.0	58.0	2.69	1184	0.068	9	
							Average	36.33	48.00	56.33	2.59	1290	0.066	15
23-Mar-10	LTM 557	G70	40	0.37	230	180	32.0	42.0	47.5	2.39	1038	0.062	12	(70%GGBS) - 111OPC+259GGBS-370 Kg/m ³ - Binder
							32.0	41.0	48.0	2.39	963	0.058	15	
							33.0	41.5	49	2.47	1040	0.060	10	
							Average	32.3	41.5	48.2	2.42	1014	0.060	12
24-Mar-10	LTM 558	G80	40	0.37	230	180	29.0	41.0	45.5	1.75	699	0.023	9	(80%GGBS) - 74OPC+296GGBS 370 Kg/m ³ - Binder
							30.0	41.0	46.0	1.78	658	0.025	10	
							27.0	45.0	44.0	1.76	803	0.020	12	
							Average	28.7	42.3	45.2	1.76	720	0.023	10
25-Mar-10	LTM 559	G90	40	0.37	200	175	20.0	30.0	35.0	1.13	741	0.015	9	(90%GGBS) - 37OPC+333GGBS 370 Kg/m ³ - Binder
							21.5	31.0	34.0	1.21	637	0.01	9	
							21.0	30.5	33.0	1.05	633	0.012	10	
							Average	20.8	30.5	34.0	1.13	670	0.012	9

Table 9 Construction Waste - Recycled water and recycled aggregate (RWRA) test results.

Recycled Water and Recycled Aggregate Test Results							COMPRESSIVE STRENGTH OF CUBES, N/mm2			DURABILITY RESULTS			
										WA, %	RCP, coulombs	ISAT, ml/m2/sec	WP, mm
Date of casting	Ref. no.	Mix Code	Target Strength	w/c	Slump, 0 min	Slump, 30 min	7 days	28 days	56 days	BS1881:122:89	ASTMC1202:97	BS1881:208:96	DIN 1048:1991 Part 5
22-Mar-10	LTM 556	G60	40	0.37	230	190	31.0	46.0	51.0	2.58	1311	0.069	13
							31.0	46.0	52.0	2.67	1400	0.065	15
							31.0	45.0	52.0	2.44	1277	0.067	13
Average							31.0	45.7	51.7	2.56	1329	0.067	14
09-Mar-10	LTM 551	G70	40	0.37	180	155	30.0	43.5	48.0	2.08	1113	0.069	12
							29.0	44.0	48.0	2.00	1039	0.063	10
							29.0	43.0	48	2.05	1028	0.063	10
Average							29.3	43.5	47.3	2.04	1060	0.065	11
10-Mar-10	LTM 552	G80	40	0.37	185	160	27.0	39.5	45.0	1.75	438	0.025	9
							26.0	38.0	45.0	1.57	468	0.025	10
							27.0	38.0	45.0	1.50	376	0.024	8
Average							26.7	38.5	45.0	1.61	427	0.025	9
11-Mar-10	LTM 553	G90	40	0.37	180	145	16.0	25.0	32.0	1.21	415	0.013	8
							16.0	24.0	33.0	1.29	436	0.013	9
							16.0	23.0	32.0	1.12	388	0.011	8
Average							16.0	24.0	32.3	1.21	413	0.012	8

had the most severe effect on bending strength, which was on the order of 29% for RA and 36% for RWRA. The current tests used OPC, thus to enhance the durability of recycled concrete, fly ash and/or GGBS must be used for any future building construction in the Gulf using such concrete to obtain high durability. However, for any pavement construction or industrial floors, OPC may be adequate.

With regard to concrete made of construction waste, it was found that the effect of RA and RW on compressive strength and durability is moderate. It was found that increasing the amount of GGBS in the recycled concrete mixes containing RW and/or RA from construction waste has beneficial effects on strength and durability. Although the mixes with 80% and 90% replacement achieved good results, the mix with 90% GGBS showed good durability performance but did not

achieve the target strength of 40 MPa even after 56 days. It was found that the G80 and G90 mixes had comparatively the smallest carbon footprint of 129.9 and 100.2 kg/m³, respectively. In general, fully recycled concrete mix (100% recycled water and recycled aggregate) with 80% GGBS replacement is recommended for future construction in the Gulf with an expected carbon footprint of 129.9 kg/m³.

Acknowledgments

The authors would like to thank Professor Takafumi Noguchi for providing information about RA in Japan, and Mr Polding Canto of MB Mix and Mr Elyas Shah of GTL for their assistance with the concrete testing. The authors would like to thank also the following students of Dubai Mens College for performing the experiments: Mr Ahmed Shabaan, Mr Ahmed al Najjar,

Fig.15 Summary of cube strength tests results for G70 (in MPa).

Fig.16 Summary of cube strength tests results for G80 (in MPa).

Table 10 Percentage reduction in axial strength and durability for DW Series and CW Series.

Property	Mix /Property		DW Series						CW Series					
			7 Days			28 Days			7 Days			28 Days		
			100% RWRA	100% RW	100% RA	100% RWRA	100% RW	100% RA	100% RWRA	100% RW	100% RA	100% RWRA	100% RW	100% RA
Axial Strength		G70	-	-	-	-	-	-	-47.20	-5.40	-41.80	-36.03	2.94	-38.97
		G80	-	-	-	-	-	-	-44.26	-4.26	-40.00	-37.10	-6.22	-30.88
		Max	-30.30	-8.80	-21.50	-29.20	-14.00	-15.20	-47.20	-5.40	-41.80	-37.10	-6.22	-38.97
Durability (28 Days)	RCP	G70	-	-	-	-	-	-	-	-	-	-122.69	-9.66	-113.03
		G80	-	-	-	-	-	-	-	-	-	-8.65	74.56	-83.21
		Max	-	-	-	-61.76	-33.10	-28.66	-	-	-	-122.69	-9.66	-113.03
	WA	G70	-	-	-	-	-	-	-	-	-	-38.78	25.85	-64.63
		G80	-	-	-	-	-	-	-	-	-	-12.59	10.49	-23.08
		Max	-	-	-	-103.45	-65.53	-37.92	-	-	-	-38.78	10.49	-64.63

* The bold values were predicted by using RA=RWRA-RW or RW=RWRA-RA

** Positive sign means the measured strength/ durability improved.

Mr Abdulaziz Al Ali, Mr Ahmed Aljazairi, and Mr Abdulla Griban. Thanks are given also to Hi Star Water Solution, MB Mix, Uni Mix, Geosciences Testing Laboratory, and Emirates Recycling. The authors thank also Mr Fransus Valdez of DMC for his assistance in making

the recycled concrete specimens. Thanks are given to Dr Leo Chaves, Mr Philip Corcos and Mr Douglas Cousino of DMC for allocating the required resources to conduct research at DMC.

Fig.17 Summary of water absorption (WA) tests results for G70 and G80 (in %).

Fig. 18 Summary of the RCP tests results for G70 and G80 (in Coulombs).

Fig.19 Selected photos from the project showing from top left (concrete cylinders, concrete cubes, cylinder under lateral load, cylinder fracture, steel reinforcing for beams, concrete mix, concrete beams, a beam under load, curing of cubes, beam moulds, RA cleaning, RW obtained from MBR process, further cleaning of RA, measuring slump, concrete cubes ready for testing, concrete cylinders ready for testing).

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