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Preface

Concrete structures are designed so that they can satisfy requirements regarding safety, serviceability, durability and aesthetics throughout their design service life.

The durability aspect is a natural extension of the classical resistance verification where deterioration effects are normally neglected. The reliability is assessed through the given performance that must be delivered within the design service life, the so-called performance-based design. This approach can be adopted for a performance based on service life design. In the recent years design is related to durability through the analysis of carbonation, resistance to chloride ingress, improved freezing and thawing resistance, etc. The review of literature and some recommendations are presented referring to the design of structures aiming to attain greater durability of concrete structures. The accent is put on the theory of reliability, failure probability and service life probability. The basics of this analysis are given through the principles of performances and service life, and deterministic and scholastic methods using the lifetime safety factor.

This book gives a basic understanding of the complex set of phenomena governing durability and long term performance of concrete structures and how this forms a basis for service-life design.

Editor

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Chapter 1

Sustainable Concrete with High Volume Ggbfs to Build Masdar City inthe Uae

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ABSTRACT

Masdar City (MC) is leading the Middle East in the development of energy and resource efficient low-carbon construction in the United Arab Emirates (UAE). One of its major goals is to develop and specify materials and processes that will help reducing its environmental footprint through resource and energy conservation, as well as renewable energy generation. In 2010 MC announced on its website a prized-competition for the best proposal of "Sustainable Concrete" and "Lowest Carbon Footprint" to build MC with a total of two million cubic meter of concrete on 4 years period. This paper presents the experimental test results of 13 types of concrete mixes made with high volume of ground granulated blast furnace slag (GGBFS) cement with 50%, 60%, 70% and 80% replacement of ordinary Portland cement (OPC) to reduce the carbon emissions. A fly ash-blended mix made with 30% fly ash was also tested. The paper provides more information on the mix design parameter, full justification of CO_2 footprint, and cost reduction for each concrete type. The hardened and plastic properties and durability test parameters for each mix are presented. The results show that the slag concrete mixes significantly reduce the carbon footprint and meet the requirements of MC. An economical mix with 80% GGBFS and 20% OPC was nominated for use in the future construction of MC with 154 kg/m^3 carbon foot print.

INTRODUCTION

General

The production of 1 tonne of Portland cement requires 1.5 tonnes of raw material. The production of Portland cement is highly energy intensive, consuming 4–7 MJ of fossil fuel energy per kg (Malhotra, 1988 and Swamy, 1998), and releases approximately 1 tonne of carbon dioxide for manufacture of each tone of Portland cement. The production of cement contributes 5% of the global greenhouse gas emissions (Collins and Sanjayan, 2002). The use of slag (GGBFS), an industrial by-product which otherwise would contribute to land pollution, as a replacement for Portland cement in concrete will result in less energy for the manufacture of cement and reduce the green gas emissions due to concrete construction (Flower et al., 2005).

Slag-blended cement, a blend of ordinary Portland cement (OPC) and ground granulated blast furnace slag ("slag") has had many years use worldwide in the construction industry. In recent years, many industrial waste by-products such as slag and fly ash are rapidly becoming the main source of supplementary cementitious materials (SCM) for use in concrete manufacture. These SCMs are well known having a significant effect on reducing the concrete permeability, when properly cured, which is the main governing property for producing durable concrete (Mehta, 1984 and Hooton, 2000) suitable for the Gulf environment where sever conditions prevail. SCMs can also be used to reduce the heat generation associated with cement hydration and reduce the potential for thermal cracking in massive structural elements. The SCMs modify the microstructure of the concrete and reduce its permeability thereby reducing the penetration of water and waterborne salts into concrete thus enhancing the service life of the structure.

The inappropriate selection of cementitious materials and admixtures in mixture proportioning could have an either significant impact on cost and/or may not achieve the properties required for producing a durable concrete (i.e. high chloride resistance).

Producing sustainable concrete with a low carbon foot print was among the aims of this research. It is well known that the production of OPC produces a carbon foot print of about 1000 kg/m3 (Malhotra and Mehta, 2008). One solution to reduce the high and unaccepted construction emissions is by replacing the cement in the concrete mix (Elchalakani and Elgaali, 2010). The ground granulated blast furnace slag (GGBFS) is widely used to replace the cement to enhance the durability (Mehta, 1984 and Hooton, 2000). The GGBFS is a by-product of the steel production process (thus it is a green material), therefore, it is used here to enhance the durability and lower the carbon foot print. Thus except for the remaining small quantity of OPC used in the concrete mix, the concrete used in this project may be termed 'sustainable concrete'. To this end, this paper reports the findings of an experimental program to provide general guidelines on designing sustainable concrete mixtures suitable for use in the future construction of Masdar City in the Gulf which is a well-known harsh environment.

Within such environment, the high ambient temperature, low humidity, drying winds and dust blown salts all present great challenge to the construction of high quality concrete in the Gulf. Accordingly, special precautions need to be instituted under these extreme ambient conditions to enhance the design life and durability of MC concrete structures in service. One approach to deal with such conditions is to use high volume GGBFS concrete to increase the setting times which is beneficial for the hot climate. The GGBFS cement particles are finer (>450 m^2/kg) than the OPC ones (<350 m^2/kg). This would reduce the amount and rate of bleeding of these concretes. The reduction in bleeding together with the increase in setting times of concrete can increase the risk of plastic shrinkage cracking and may warrant special precautions during placing and finishing operations. Plastic shrinkage usually occurs within 10–12 h after placement only when concrete is exposed to unsaturated air (RH < 95%) in the presence of high speed wind and hot temperature (Collepardi, 2006 and ACI Manual, 2005).

Masdar City Requirements

Masdar City (MC) is a relatively new origination based in the UAE and is leading the Middle East in the development of energy and resource efficient low-carbon construction. One of its major goals is to develop and specify materials and processes that will help reducing its environmental footprint through resource and energy conservation, as well as renewable energy generation. In 2010 MC announced on its website a prized-competition for the best proposal of "Sustainable Concrete" and "Lowest Carbon Footprint" to build MC with the following requirements.

1. Total CO_2 emission per cubic meter of concrete should be less than Masdar baseline mix which has a carbon footprint of 192 kg/m^3.
2. Total cost of all constituent materials required per cubic meter of concrete comparable with Masdar baseline mix which has a cost of 211 AED/m^3 (1.0 USD = 3.679 AED).
3. Production capacity is anticipated at 500,000 m^3 per year for four years.
4. Concrete performance for proposed mix design, including but not limited to:

- *Workability*: slump and slump retention. A minimum slump of 150 mm is required.
- Compressive strength at 28 days not less than 40 MPa.
- *Durability*: rapid chloride penetration less than 1000 C at 28 days.

- *Hot weather*: maximum temperature of fresh concrete of 35 °C.
- *Temperature rise*: maximum concrete temperature of less than 70 °C.

This paper presents the recent research findings of 14 controlled laboratory trial mixes. It will be discussed how such mixes reduce the carbon footprint and could meet the requirements of MC. The paper provides more information on the mix design parameter, full justification of CO_2 footprint, and cost involved. The hardened and plastic properties and durability test parameters for each mix are also presented and discussed.

TEST PROGRAM

Material Properties

Table 1 shows the chemical composition of the General Portland cement type CEM I 42.5 N complying with BS EN 197-1 (2000) GP and the ground granulated blast furnace slag (GGBFS) complying to BS 6699 (1992) and fly ash to ASTM C618 Class F. The nominal target strength of concrete was 40 MPa at 28 days. Standard cubes 100 mm × 100 mm × 100 mm were prepared to BS 1881-116 (1983) and moist cured in a water tank at temperature of 25 °C. Several tests were performed to measure the durability parameters of the concrete namely rapid chloride penetration (RCP) test to ASTM C1202-97 (1997), chloride migration coefficient to NBuild 492 (1999), drying shrinkage to ASTM C157/C (2006), and water absorption (WA) test to BS 1881-122 (1983).

Table 1: Chemical composition of GP and GGBS

Constituent/property (%)									
	SiO_2	Al_2O3	Fe_2O_3	CaO	MgO	Mn_2O_3	SO_3	S	Cl
PC-CEM I 42.5 N BS EN 197 (2000)	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
FA-ASTM C618 Class F	70 (min)			–	–	–	5.00	N/A	–

Concrete Mix Proportions

The MC control mix had 148 kg/m³ OPC, 222 kg/m³ GGBFS, 137 kg/m³ of DEWA fresh water, 720 kg/m³ of 20 mm crushed RAK rock, 350 kg/m³ of 10 mm crushed RAK rock, 580 kg/m³ of 5 mm crushed RAK rock, and 300 kg dune sand. A high range water reducer addition of 4500 g/m³ was used in the mix. The water/cement (w/c) ratio was 0.37 and the GGBFS amount represented 60% OPC replacement. The term cement refers to the binder including OPC, FA and GGBFS. Three approaches were adopted in this study to obtain better performance than that of the baseline mix. The use of high percentages of GGBFS with low water cement ratios and medium to low total cement content was the main factor used in the design mix for each group. The first approach (Group M) was to use medium cementitious material (CM) content with a total amount of 360 kg/m³ with different w/c ratios in the range of 0.35–0.42. This approach was represented in Mixes #1, 2, 3, 4, 5, and 10. Table 2 shows the mix proportion and test results for these later mixes. The second approach (Group H) was to use a comparatively high content with a total amount in the range of 400–440 kg/m³ with the same w/c of 0.38 and variable GGBFS content in the range of 70–80%. This approach was represented in Mixes no. 6, 7, 8, and 9. Table 3 shows the mix proportion and test results for these later mixes. The third approach (Group L) was to use very low binder content in the range of 300–340 kg/m³ with different w/c ratios. This approach was represented in Mixes 11, 12, 13, and 14. Table 2 shows the mix proportion and workability test results for all mixes. Table 4 shows the mix proportion and test results for these later mixes.

Table 2: Group M. Trial mixes with medium cement content of 360 kg/m^3

Total cement content: 360 kg							
	Trial mix	1	2	3	4	5	10
	Ref. mix	1227	1228	1229	1230	1231	1236
General details	Grade (N)	40	40	40	40	40	40
	Cement (kg)	360	360	360	360	360	360
	GGBS %	0	70%	80%	80%	80%	50%
	Fly ash %	–	–	–	–	–	30%
	w/c	0.38	0.38	0.38	0.35	0.42	0.38
	Admixture (g/m^3)	8800	8200	6800	9200	6000	5200
Slump (mm)	Initial	195	235	200	220	235	210
	30 min	185	240	80	230	175	185
	60 min	150	245	45	230	75	140
Temperature (°C)	Initial	29.5	28.0	28.0	26.5	27.0	26.5
	30 min	27.5	27.0	27.0	26.0	25.5	25.5
	60 min	27.0	26.5	26.5	24.5	24.5	25.0
Average-compressive strength (N/mm^2)	1 day	26.0	9.3	9.3	11.3	9.5	7.0
	3 days	57.0	35.5	32.8	36.5	28.0	28.5
	7 days	63.0	55.5	50.3	54.8	41.0	37.3
	28 days	74.3	68.0	66.0	68.3	54.0	51.3
Durability (28 days)	RCP (C)	1971	465	397	383	402	331
		1732	486	411	377	409	314
	Water absorption %	1.62	1.49	1.35	1.24	1.68	1.05
		1.67	1.45	1.46	1.09	1.71	1.16
Carbon	Carbon (kg/m^3)	386	183	153	154	153	147
Cost (AED)	Cost (AED)	222	229	223	235	220	217

Table 3: Group H. Trial mixes with high volume cement content of 400–440 kg/m^3

High volume cement content: 400 kg and 440 kg					
	Trial mix	6	7	8	9
	Ref. mix	1232	1233	1234	1235
General details	Grade (N)	40	40	40	40
	Cement (kg)	400	400	440	440
	GGBS %	70%	80%	70%	80%
	Fly ash %	–	–	–	–
	w/c	0.38	0.38	0.38	0.38
	Admixture (g/m^3)	5200	5600	5000	5200
Slump (mm)	Initial	215	235	230	220
	30 min	100	220	195	110
	60 min	35	115	60	40
Temperature (°C)	Initial	26.0	27.0	26.5	26.5
	30 min	25.0	25.5	25.0	25.0
	60 min	24.5	24.5	24.6	24.5
Average-compressive strength (N/mm^2)	1 day	11.8	9.0	9.5	9.0
	3 days	33.3	34.5	35.3	32.0
	7 days	49.8	43.0	43.8	37.5
	28 days	60.8	56.3	55.8	49.5
Durability (28 days)	RCP (C)	551	329	525	479
		553	364	513	491
	Water absorption %	1.58	1.67	1.65	1.90
		1.77	1.75	1.55	1.96
Carbon	Carbon (kg/m^3)	196	164	209	176
Cost (AED)	Cost (AED)	223	227	231	234

Table 4: Group L. Trial mixes with very low cement content of 300–340 kg/m^3

Low cement content: 300 kg and 340 kg (60% GGBS)					
	Trial mix #	11	13	12	14
	Ref. mix	1237	1237 B	1238	1238 B
General details	Grade (N)	40	40	40	40
	Cement (kg)	340	340	300	300
	GGBS %	60%	60%	60%	60%
	Fly ash %	–	–	–	–
	w/c	0.40	0.38	0.40	0.38
	Admixture (g/m^3)	7600	7500	9200	8590
Slump (mm)	Initial	225	230	225	215
	30 min	220	235	220	235
	60 min	210	240	220	215
Temperature (°C)	Initial	27.5	30.5	27.0	31.0
	30 min	26.5	29.5	26.0	30.0
	60 min	26.0	29.0	25.5	29.5
Average-compressive strength	1 day	12.8	–	18.0	–
	3 days	41.0	–	36.3	–
	7 days	52.5	61.8	48.0	56.8
	28 days	67.5	78.5	65.5	72.5
Durability (28 days)	RCP (C)	631	522	1421	504
		595	549	1606	481
	Water absorption %	1.40	1.36	1.17	0.96
		1.39	1.34	1.19	0.93
Carbon	Carbon (kg/m^3)	202	202	184	184
Cost	Cost (AED)	220	219	217	214

TEST RESULTS

Group M (360 Kg/M³)

Fig. 1 and Fig. 2 show the results of compressive strength development for Group M which includes Mixes #1, 2, 3, 3, 5, and 10 where the total binder content is constant at 360 kg/m³. As expected Mix 1 with 0% OPC replacement had the highest mechanical strength rate while Mix 10 had the lowest rate with 50% FA + 30% GGBFS (80% OPC replacement). The 28-day compressive strength was 74.3 and 51.3 MPa, for Mix 1, and 10, respectively. Mix 4 with 80% GGBFS (w/c = 0.35) had relatively good compressive strength rate and achieved 68.3 MPa strength at 28-day of concrete age. Mix 5 with 80% GGBFS (w/c = 0.42) had relatively low compressive strength rate (54 MPa strength at 28-day). It is obvious from the results that Mix 4 had good compressive strength performance due to the lowest w/c ratio in the mix.

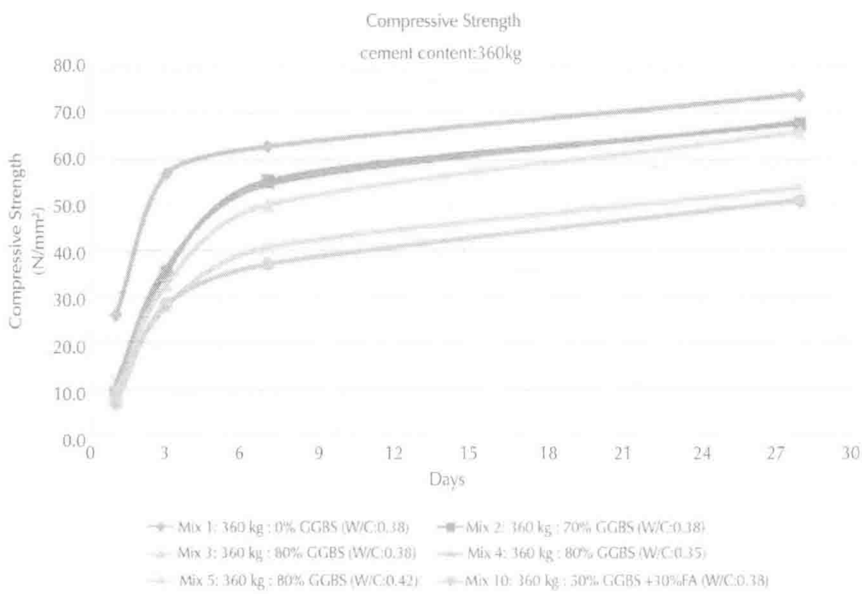

Figure 1: Mechanical strengths for Group M (360 kg/m³).