Chapter 5
Sustainability with Ultra-High Performance and Geopolymer Concrete Construction

Tian Sing Ng, Yen Lei Voo, and Stephen J. Foster

Abstract This paper presents an overview on the use of high performance cementitious products and in using cement replacement materials, such as geopolymers in the development of sustainable design and construction. The design approach not only accounts for the limit states design, it also takes into consideration the environmental impact and durability of the designed structure. Two examples of environmental impact calculations, a bridge structure and a retaining wall, are provided for conventional Portland cement concrete, geopolymer concrete and reactive powder concrete solutions. The comparison studies show that many structures constructed of reactive powder concrete and of geopolymer concrete can provide for environmentally sustainable alternatives to the use of conventional concrete construction with respect to the reduction of CO_2 emissions, embodied energy and global warming potential. The enhanced durability of reactive powder concrete and geopolymer concrete also provides for significant improvements in the design life, further supporting the concept of sustainable development.

T.S. Ng (✉) • S.J. Foster
Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, UNSW, Sydney, NSW 2052, Australia
e-mail: tian.ng@unsw.edu.au; s.foster@unsw.edu.au

Y.L. Voo
Dura Technology Sdn Bhd, Lot 304993, Jalan Chepor 11/8, Pusat Seramik, Fasa 2, Ulu Chepor, 31200 Chemor, Perak, Malaysia
e-mail: vooyenlei@dura.com.my

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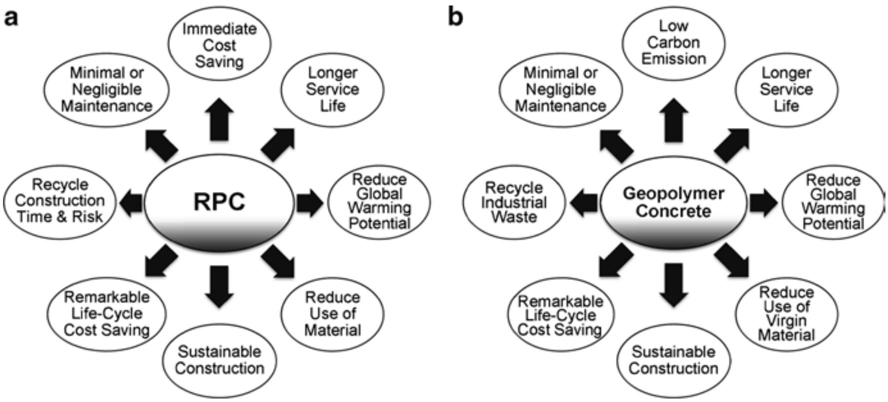

Fig. 5.1 (**a**) RPC and (**b**) Geopolymer concrete towards sustainable construction

5.1 Introduction

From the time when Portland cement was invented, the cement and concrete industry has been confronted with the environmental and energy intensive issues (Fling 1975). Both of these issues have resurfaced as a point of international interest as the world begins to move towards the concept of sustainable development. As governments develop low carbon policies, industries that consume excessive energy and/or resources are likely to be subjected to higher pricing policies to encourage market development of more sustainable solutions. The cement and concrete industry is one of these industries.

Over the last three decades, significant advancements have been achieved in the concrete industry. One of the major breakthroughs in the 1990s was the development of ultra-high performance concrete (UHPC), also known as the reactive powder concrete (RPC), by Richard and Cheyrezy (1994). Compressive strength and flexural strength of over 180 and 30 MPa, respectively, have been reported for RPC. The second advancement was the development of geopolymer and its application in concrete industry as an alternative binder to the Portland cement. Geopolymer is a material resulting from the reaction of a source material that is rich in silica and alumina with alkaline solution. Concrete made from geopolymer has also been found to be more durable than Portland cement concrete, possesses excellent engineering properties and has a lower carbon footprint than conventional Portland cement concrete (Li et al. 2004; Gourley and Johnson 2005; Rangan 2008). In the last decade, or so, extensive research has been undertaken by academics and engineers alike with the view to industrialise these technologies as alternatives for more sustainable construction. The principle of sustainable construction stands on a basis of material optimisation together with structural design optimisation, which results in the lower life-cycle cost. Figure 5.1 shows some of the immediate and long-term benefits that RPC and geopolymer concrete technology is able to provide.

This paper firstly presents an overview on the material characteristics of typical RPC and geopolymer concrete and compares them to conventional normal strength and high strength concretes. Secondly, a sustainability design approach is proposed. This design approach not only accounts for the limit states design of a structure but also takes into consideration the environmental impact and durability of the detailed structure. Examples on the environmental impact calculation (EIC) of conventional concrete structures are compared against comparable structures built using RPC geopolymer concrete. Lastly, durability aspects of each material are discussed and design calculations presented.

5.2 Material Characteristics

Table 5.1 summarises the material characteristics of RPC and geopolymer concrete and is compared against conventional, normal, strength concrete (NSC) and high strength concrete (HSC).

5.2.1 Reactive Powder Concrete

Reactive powder concrete (RPC) is suitable for use in the production of precast elements for civil and structural engineering and architectural applications. The constituent materials of RPC are ordinary Portland cement, silica fume, fine aggregate, water, steel fibres and a superplasticiser admixture. In order to achieve the required performance of RPC, powder materials and fine aggregates are blended or proportioned to an adequate particle size distribution in order to maximise the density or compactness. Table 5.2 presents the mix design for a standard RPC with 2% steel fibres by volume of concrete. The superplasticiser used is Polycarboxylate ether (PCE)-based and no recycled wash water is used in the mixing. In addition, structural members made of RPC are recommended to be heat cured for a minimum of 48 h at a temperature of 90°C by the concrete committee of the Japanese Society of Civil Engineering recommendations for design and construction of ultra-high strength fibre reinforced concrete structures (JSCE 2006).

Reactive powder concrete is a highly homogenous cementitious-based composite without coarse aggregates and, therefore, can achieve ultra-high compressive strengths and high flexural strength. Its blend of very high strength steel fibres and cementitious binders with extremely low water content give RPC extraordinary characteristics of mechanical strengths and high ductility. The durability of RPC is comparable to natural rocks with very low permeability and is resistant to carbonation (Xie et al. 2008). After early age heat treatment, there is almost no shrinkage or creep, which makes RPC very suitable for applications in prestressed concrete. The use of this material for construction is simplified through the elimination or minimization of conventional reinforcing steel and the ability of the material to be

Table 5.1 Material characteristics of RPCs and Geopolymer concretes compared to normal strength (*NSC*) and high strength (*HSC*) Portland cement concrete (after Graybeal 2006; Muntingh 2006; Rangan 2008; Ng and Foster 2008; Poon et al. 2009; Voo and Foster 2010)

Characteristics	Unit	Code/standards	NSC	HSC	Geopolymer concrete	RPC
Specific density, ρ	kg/m^3	AS1012.12.1 (1998)	2,300–2,400	2,400–2,500	2,250–2,400	2,350–2,550
Cylinder compressive strength, f_{cy}	MPa	AS1012.9 (1999)	20–50	50–100	30–100	120–210
Creep coefficient at 28 days, ϕ_{cc}		AS1012.16 (1996)	2–5	1–2	<0.7	0.2–0.66
Post cured shrinkage	με	AS1012.13 (1992)	1,000–2,000	500–1,000	≈100	<100
Modulus of elasticity, E_c	GPa	AS1012.17 (1997)	20–35	35–40	20–35	40–53
Poisson's ratio, ν		AS1012.17 (1997)	0.2	0.2	0.15–0.2	0.18–0.2
Split cylinder cracking strength, f_t	MPa	BS:EN 12390–6 (2000)	2–4	2–4	N/A	5–12.4
Split cylinder ultimate strength, f_{sp}	MPa	AS1012.10 (2000)	2–4	4–6	2–7.5	10–26.5
Flexural first cracking strength, $f_{cr,4P}$	MPa	AS1012.11 (2000),	2.5–4	4–8	2.5–8	8–9.7
Modulus of rupture, $f_{cf,4P}$	MPa	ASTM C1018 (1997)	2.5–4	4–8	2.5–8	18–50
Toughness indexes, I_5		(four-point test on	1	1	1	4–6.2
Toughness indexes, I_{10}		un-notched	1	1	1	10–15
Toughness indexes, I_{20}		specimen)	1	1	1	20–35
Bending fracture energy, $G_{f,\delta=0.46\,mm}$	N/mm	JCI-S-001 (2003),	<0.1	<0.2	<0.2	1–2.5
Bending fracture energy, $G_{f,\delta=3.0\,mm}$	N/mm	JCI-S-002 (2003)	<0.1	<0.2	<0.2	10–20
Bending fracture energy, $G_{f,\delta=10\,mm}$	N/mm		<0.1	<0.2	<0.2	15–30
Rapid chloride permeability	Coulomb	ASTM C1202 (2005)	2,000–4,000	500–1,000	N/A	<200
Chloride diffusion coefficient, D_c	mm^2/s	ASTM C1556 (2004)	$4–8 \times 10^{-6}$	$1–4 \times 10^{-6}$	$<0.003 \times 10^{-6}$	$0.05–0.1 \times 10^{-6}$
Water absorption	%	BS 1881:Part 122 (1983)	>3	1.5–3.0	<2	<0.2

Table 5.2 Mix design of typical (**a**) RPC and (**b**) geopolymer concrete

	Mass (kg/m^3)	
Ingredient	RPC	Geopolymer concrete
Portland cement	720	–
Silica fume	180	–
Fly ash	–	240
Ground granulated blast furnace slag	–	42
Fine aggregate	1,150	695
Coarse aggregate	–	1,120
Superplasticiser	40	–
High strength steel fibres	157	–
Free water	144	91
Sodium hydroxide (NaOH) solid	–	15.5
Sodium silicate solution (with $SiO_2/Na_2O=2$)	–	110

virtually self-placing or dry-cast. The comparison in Table 5.1 shows that RPC has superior mechanical properties over normal and high strength concretes.

5.2.2 Geopolymer Concrete

Geopolymer concretes have emerged as novel engineering materials with the potential to form a substantial element of an environmentally sustainable construction and building products industry (Provis et al. 2005; Duxson et al. 2007). Geopolymer concretes are commonly formed by alkali activation of industrial aluminosilicate waste materials such as fly ash and blast furnace slag, and, as will be discussed in detail in this paper, have lower greenhouse footprint when compared to traditional Portland cement concretes. Table 5.2 presents the mix design for a typical geopolymer concrete developed at the University of New South Wales, Australia.

With correct mix design and formulation development, geopolymer concrete can provide superior chemical and mechanical properties to Portland cement concrete, and be highly cost effective. Geopolymer concrete can gain 70% of the final compressive strength in the first four hours of setting (Li et al. 2004; Rangan 2008). Rangan (2008) and at the University of New South Wales, fly ash based geopolymer concretes have been developed with an achievable compressive strength ranging from 8 to 100 MPa depending on the mix composition and curing method. Similar to RPC, structural members made of geopolymer concrete are recommended to be heat cured (Rangan 2008).

Comparing geopolymer concrete with conventional concrete, heat treated geopolymer concrete has low shrinkage and creep (van Jaarsveld et al. 1997; Rangan 2008) and has a superior chemical resistance against chlorides, sulphates and acids (Palomo et al. 1999; Muntingh 2006; Song 2007; Rangan 2008). Geopolymer concrete is also found to have high fire resistance in accordance with the studies of Gourley and Johnson (2005) and Kong and Sanjayan (2010). Importantly though, geopolymer concrete is found to have moderate to low elastic modulus for its strength (Fernández-Jiménez et al. 2006; Rangan 2008; Ng and Foster 2008).

5.3 Sustainability Design Approach

The concept of sustainability design, commonly known as "green design" as defined by the US Green Building Council (USGBC), consists of three components: environmental, economic, and health and community benefits. All three of these components can benefit from choices made in the structural design and construction phases of a project. The following is a list of the environmental, economic, and health and community benefits offered through sustainable structural design and construction as defined by the USGBC:

- Improvement and protection of the environment and biodiversity;
- A decline of solid waste products;
- Conservation of natural resources;
- A decrease in energy consumption with an increase in energy savings;
- Improved durability of structures and savings in project life cycle costs;
- A reduction in maintenance costs; and
- Improvement of occupant health and comfort.

The approach used for the design of RPC and geopolymer concrete structures is presented in Fig. 5.2. The three fundamental criteria for assessment of a sustainable design are:

1. An environmental impact calculation (EIC);
2. Design for longevity (i.e. durable structures);
3. Limit states design.

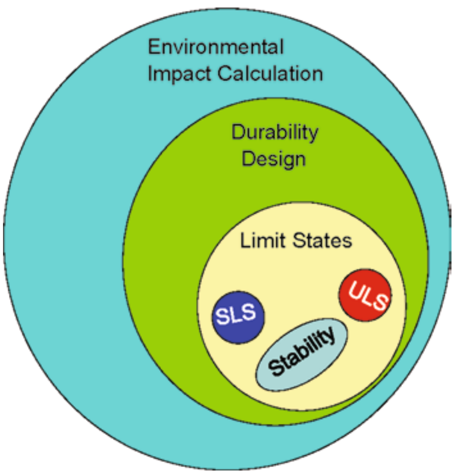

Fig. 5.2 Design model

Table 5.3 Environmental data for an EIC

	Units	RPC (2% steel Fibres)[a]	Grade-60 (15% PFA)	Grade-60 (15% PFA)	Geopolymer concrete	Steel Reinforcement
Density	kg/m^3	2,400	2,350	2,350	2,350	7,840
EE	GJ/m^3	7.77	2.70	2.27	0.57	185.8
CO_2	kg/m^3	10.65	487.2	406.8	318.2	17,123
NO_x	kg/m^3	4.86	1.66	1.66	–	55.4
CH_4	kg/m^3	0.76	0.12	0.12	–	30.7
100-year GWP	kg CO_2 eq./m^3	2,537	985	905	318	34,392
EE	MJ/kg	3.24	1.15	1.03	0.24	23.70
CO_2	kg/kg	0.45	0.21	0.17	0.14	2.18
NO_x	g/kg	2.03	0.71	0.71	–	7.06
CH_4	g/kg	0.32	0.05	0.05	–	3.91
100-year GWP	kg CO_2 eq./kg	1.06	0.42	0.38	0.14	4.39

[a]Environmental values include steel fibres contribution

To assess the performance of a structural design with regards to sustainability, objective measures are needed. For example, the EIC is a measure of the optimisation of the materials used with respect to the embodied energy, CO_2 emission and global warming potential when compared to existing practice. Durability can be defined as the capability of a structure to meet its defined design serviceability and strength limit state criteria over time. Durability design is important to ensure the designed structure meets the required design life, within a designed maintenance plan, thereby reducing the overall life-cycle cost, social impact and unplanned additional material consumption, which can bear heavily on future carbon impacts. Thus, in this paper durability design is categorized as a sub-set of environmental impact design. Finally, the limit state design should be used to design the structure to satisfy serviceability, stability and strength requirements. By fulfilling the aforementioned criteria, the overall cost and functionality of a designed structure will be optimised with respect to minimising its environmental impact.

5.3.1 Environmental Impact Calculation (EIC)

Undertaking a full EIC is a complex exercise and the data required for the calculation vary from country to country due to local practices and available technologies. Table 5.3 summarises the environmental data used in this comparative study. The table has been prepared for determining the equivalent CO_2 content of particular concrete mix designs and materials and the information may be updated frequently as the industry continues to improve its processes. The values of embodied energy (EE) and CO_2 emission in the production of the Portland cement concrete and steel for this study are extracted from the work of Struble and Godfrey (2004), while for geopolymer concrete the work of Witherspoon et al. (2009) is adopted. The energy

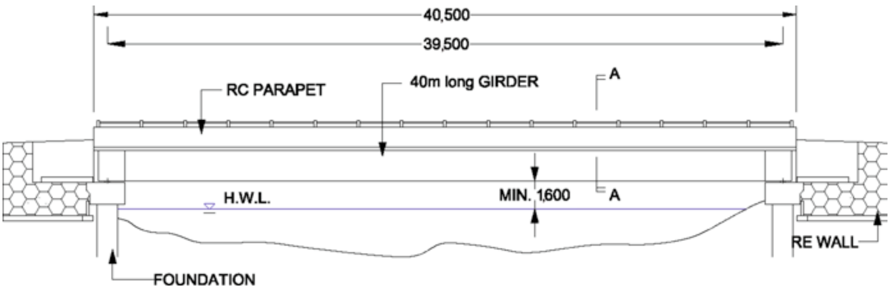

Fig. 5.3 Layout of a 40 m long span concrete road bridge

consumed in the production of Portland cement is estimated to be 4.88 MJ/kg and the total energy in the production of steel is estimated to be 23.7 MJ/kg (i.e. 185.8 GJ/m^3) (Struble and Godfrey 2004). For geopolymer concrete, the production of the alkaline source required to activate the fly ashes is the most energy intensive component in the manufacturing process. The energies consumed in the production of NaOH and sodium silicate are estimated to be 14.6 and 8.6 MJ/kg, respectively (Witherspoon et al. 2009). Based on these values, the EE values of Grade-40 and Grade-60 Portland cement concretes and that of geopolymer concrete and RPC with 1.5% and 2% of steel fibres can be determined and are presented in Table 5.3.

Elrod (1999) defines Global Warming Potential (GWP) as a measure of how a given mass of greenhouse gas is estimated to contribute to global warming over a given time interval. It is a relative scale that compares the gas in question to that of the same mass of CO_2 and a 100-year of time horizon is most commonly adopted, as per the Kyoto Protocol (Forster et al. 2007). The formulation of GWP can be ambiguous and the adequacy of the GWP concept has been widely debated since its introduction (Fuglestvedt et al. 2003). For simplicity, the 100-year GWP can be expressed as:

$$100-\text{year GWP} = CO_2 + 298\ N_2O + 25\ CH_4 \tag{5.1}$$

In the concrete industry, the production of Portland cement is the main contributor to the GWP. The greenhouse gas emission associated with the production of 1 tonne of Portland cement has been estimated at approximately 0.8 to 1 tonne of CO_2 and an average of 3.5 kg of Nitrogen oxides (NO_x) (Huntzinger and Eatmon 2009; US EPA 1994).

5.3.2 *Sustainability Design Example 1: Single Span 40 m Concrete Road Bridge*

Figure 5.3 shows the layout of a single span 40 m concrete bridge used by Voo and Foster (2010) to assess the GWP of RPC. In this paper, the design is supplemented by a geopolymer concrete and the I-girder section design (commonly adopted in

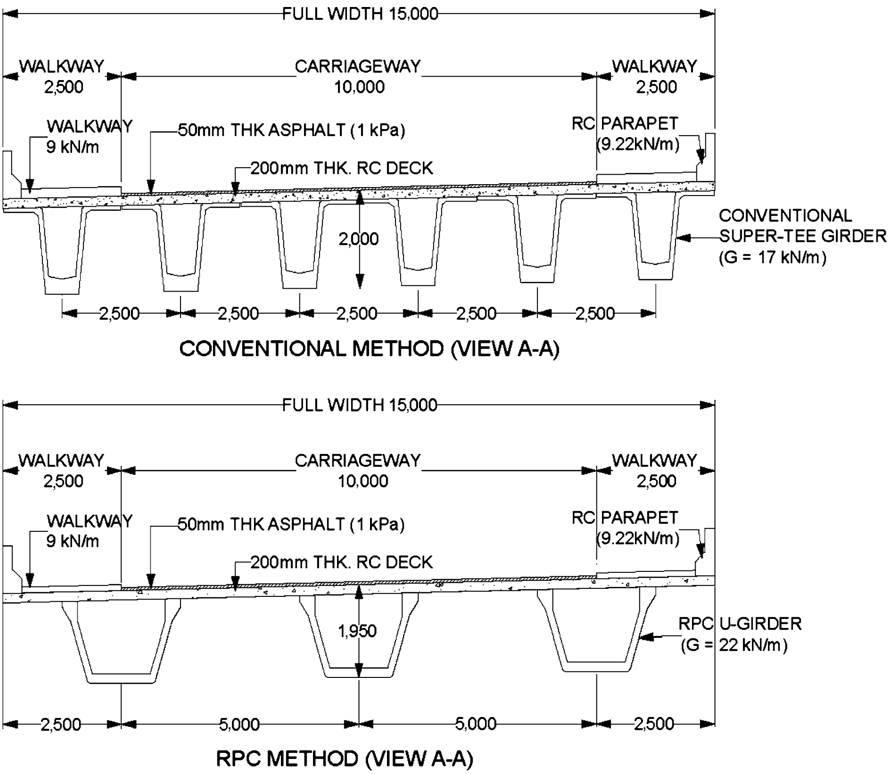

Fig. 5.4 Comparison of cross sectional view for conventional Super-T girders design and RPC U-girder design

Malaysia) is replaced with Australian super-tee sections. Note that the super-tee designs generally provide for the most economical solution using current practice. The total transverse width of the bridge is 15 m. Based on conventional concrete design, six precast pre-tensioned super-tee girders are needed. For the alternative RPC design, three U-girders are used (see Fig. 5.4). In this example, the precast girders are designed to be simply supported at their ends and are composite with a 200 mm thick Grade-40 in-situ RC deck slab. The RC deck is then covered with a 50 mm thick asphalt wearing surface as is common Australian practice.

The bridge is designed for the following specifications:

- Design life: 120 years
- Exposure class: XS1-exposed to airborne salt but not in direct contact with sea-water (Eurocode 2 (CEN 2004), Table 4.1)
- Imposed live load: Load models 1–4 with special vehicle 1800/150 (Eurocode 1-Part2 (CEN 2001))
- Minimum free-board clearance: 1.6 m
- Superstructure: Precast girders with 200 mm thick composite in-situ RC deck slab
- Bridge length: Single span of 40 m

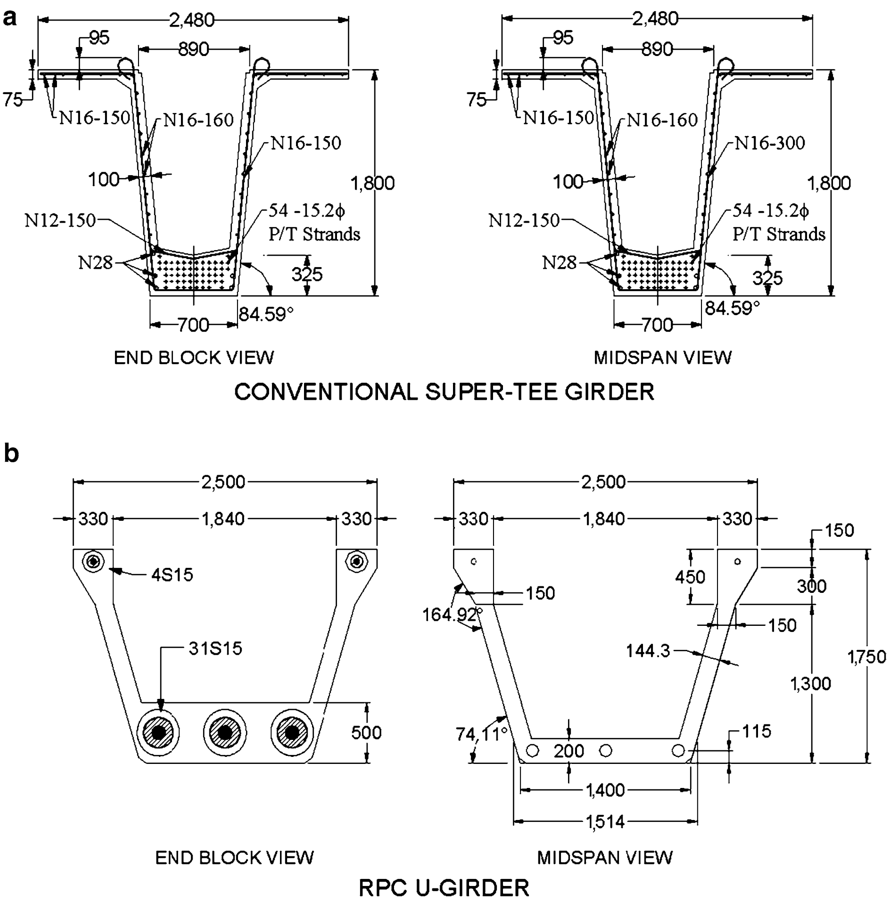

Fig. 5.5 Dimension of (**a**) conventional Super-T girders design and (**b**) RPC U-girder bridge

- Supported length: 39.5 m (centre-to-centre of bearings)
- Overall bridge width: 15 m
- Cross slope: 2.5%.

Figure 5.5a shows the cross section details for the 40 m long conventional super-tee girder design. The girders are designed to AS5100.5 (2004) Type 5 category and are pre-tensioned with 54 by seven wire low relaxation strands of nominal diameter 15.2 mm and nominal strength of 1,790 MPa and conformed to AS 4672.1 (2007). The strands are stressed to 75% of their guaranteed ultimate tensile strength (GUTS).

In this example, conventional steel reinforcing bars in the web are used to transfer shear forces and to resist transverse bending moment on the top flanges. The girder weighs approximately 1.7 tonnes per metre and gives a total weight of 68 tonnes per 40 m girder. In contrast, Fig. 5.5b gives the detail of the alternative

DURA® -U1750 RPC precast girder adopted for the RPC solution. The RPC girder consists of two 150 mm thick webs, a 200 mm thick base and it is post-tensioned using three tendons of 31 by 15.2 mm diameter strands at the base and two tendons of four by 15.2 mm diameter strands at the top flanges to ensure that the joints are in compression during transfer and in service. Each girder comprises five segments (three 8 m internal segments and two 8 m end-block segments). In addition, unlike a conventional precast concrete girder, the webs do not contain any reinforcement for transverse shear forces with steel fibres included to carry the tensile component of the internal forces generated by shear (Voo et al. 2006; Voo and Foster 2009). The girder weighs 2.2 tonne/m, which gives a total of 88 tonnes per girder.

Table 5.4 summarises the material quantities and the EIC of the two bridge girder designs. In the calculation of the material quantity, only the superstructure is considered herein. The amount of EE, CO_2 emissions and 100-year GWP are obtained from multiplying the amount of materials by the environmental data given in Table 5.3. A comparison of the EIC results is presented in Fig. 5.6. In terms of material consumption, the RPC design solution consumed 37% less material than the conventional solution. In terms of environmental impact, the RPC solution has 14% less embodied energy and 12% less CO_2 emissions. In terms of the 100-year GWP, the RPC solution provides for a reduction of 10% over that of the conventional solution.

For the geopolymer concrete solution, the design is similar to that Portland cement concrete and, therefore, the total material consumption is similar. However, in terms of natural resources or virgin materials consumption, geopolymer concrete is 8% lower that Portland cement concrete as it utilises industrial waste products such as fly ashes and slags that would otherwise be dumped into landfill sites or flushed into the sea. The geopolymer concrete solution consumes 15% less energy and gives 14% lower CO_2 emissions than the conventional Portland cement concrete design. Its 100-year GWP is 35% and 25% lower than that of Portland cement concrete and RPC solutions, respectively.

In regards to the above calculations for sustainability, it also needs to be recognised that only the savings at the level of the superstructure have been considered. For the RPC design solution, significant further savings will result from the lighter weight of the super-structure giving a smaller sub-structure, foundations and lower transport costs.

5.3.3 Sustainability Design Example 2: 1.5 m High Retaining Wall

A 180 m long by 1.5 m high retaining wall was recently developed as a pilot application of RPC technology in the construction of a 90 m long monsoon drain for a housing development project in Ipoh, Malaysia (Fig. 5.7a). The design surcharge load is 10 kPa at service and 15 kPa at ultimate. For a conventional reinforced concrete L-shaped wall, the wall will have a minimum of 150 mm thick footing and 100–150 mm thick stem (Fig. 5.7c). For the RPC solution, the L-shaped wall

Table 5.4 Material quantities and EIC for 40 m long road bridge

	RPC (m^3)	Grade-60 OPC concrete (m^3)	Grade-40 OPC concrete (m^3)	Geopolymer concrete	Steel reinforcement
Conventional design (OPC concrete)					
Precast 40 m super-tee girders	0	173.26	0	0	53.17
End crosshead (inc. wing-wall, approach slab and diaphragm)	0	0	124.9	0	16.61
RC deck (total) – 1.5% Reo.	0	0	120	0	14.1
RC Parapet – 1.0% Reo.	0	0	31.3	0	2.45
Sub-total	0.0	173.3	276.2	0.0	86.4
Mass of material used (tonne)	0	407.2	649.1	0	86.4
Embodied energy (GJ)	0	468	627	0	2,046
CO_2 (tonne)	0	84	112	0	188
GWP (tonne CO_2 eq.)	0	171	250	0	379
Conventional design (Geopolymer concrete)					
Precast 40m super-tee girders	0	0	0	173.26	53.17
End crosshead (inc. wing-wall, approach slab and diaphragm)	0	0	0	124.9	16.61
RC deck (total) – 1.5% Reo.	0	0	0	120	14.1
RC Parapet – 1.0% Reo.	0	0	0	31.3	2.45
Sub-total	0.0	0.0	0.0	449.5	86.4
Mass of material used (tonne)	0	0	0	1056.3	86.4
Embodied energy (GJ)	0	0	0	602	2,046
CO_2 (tonne)	0	0	0	143	188
GWP (tonne CO_2 eq.)	0	0	0	143	379
RPC design					
Precast 40m DURA-U1750 girders	108	0	0	0	17.1
End crosshead (inc. wing-wall, approach slab and diaphragm)	0	0	103	0	16.61
RC deck (total) – 1.5% Reo.	0	0	120	0	14.1
RC Parapet – 1.0% Reo.	0	0	31.3	0	2.45
Sub-total	108.0	0.0	254.3	0.0	50.3
Mass of material used (tonne)	257.9	0	597.6	0	55
Embodied energy (GJ)	835.0	0	577	0	1,304
CO_2 (tonne)	115.5	0	103	0	120
GWP (tonne CO_2 eq.)	274	0	230	0	220

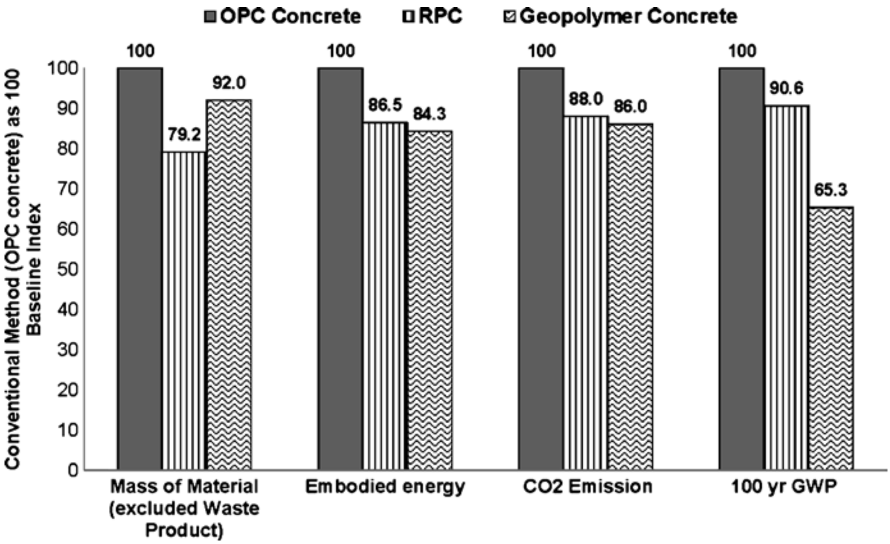

Fig. 5.6 EIC comparison for 40 m span bridge

required only thin panels of 30–50 mm thick (Fig. 5.7d) and weighs just 260 kg/m, a factor of four times lighter than the conventional reinforced concrete solution. The RPC wall was proof loaded with back filled soil up to 1.5 m and with an additional surcharge load of 25 kPa (Fig. 5.7e), 66% greater than the strength limit requirement and still it did not fail!

A comparison of the EIC results of the RPC retaining wall system against the conventional L-shaped retaining wall using Portland cement concrete and geopolymer concrete is given in Voo and Foster (2010) and presented in Fig. 5.8. In terms of material consumption, the RPC retaining wall consumes 76% less material than the conventional Portland cement concrete wall. In terms of the environmental indexes, the RPC wall requires less embodied energy and produces 48% less CO_2 emissions. In terms of the 100-years GWP, the RPC solution provides a reduction of 35%.For the geopolymer concrete solution, again less virgin materials are consumed than for the Portland cement design, it has 25% lower embodied energy and 20% less CO_2 gases are emitted. The geopolymer concrete solution has the least 100-year GWP in comparison with conventional Portland cement concrete and RPC solution.

5.4 Durability Design

The current design method for durability of concrete is based on deem-to-satisfy rules (i.e. minimum cover and crack width limitations) and the assumption that if these rules are met, the structure will have an adequate service life. However, many reinforced concrete structures deteriorate due to premature corrosion of steel

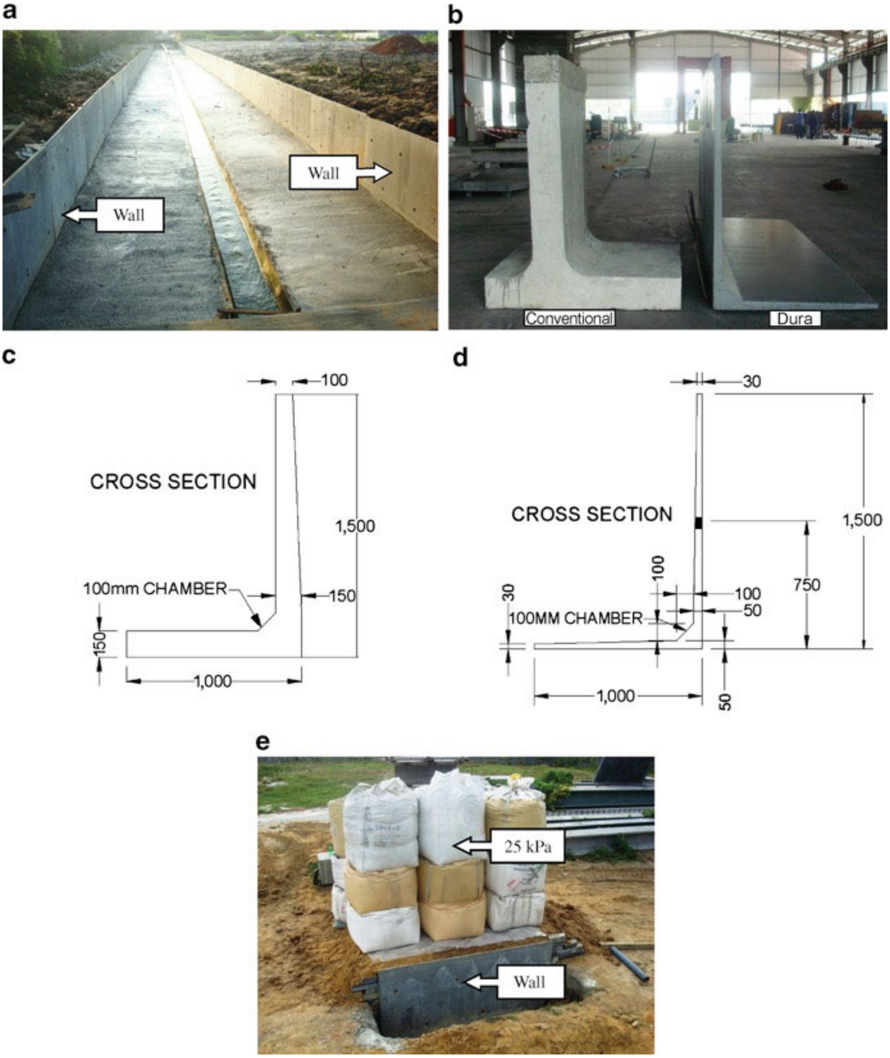

Fig. 5.7 (**a**) 90 m long monsoon drain using RPC retaining wall in Malaysia, (**b**) comparison of conventional precast L-shape retaining wall against RPC light weight retaining wall, (**c**) cross sectional details for conventional precast L-shape retaining wall, (**d**) cross sectional details for RPC retaining wall, and (**e**) load proof test of the RPC wall back filled and with a 25 kPa surcharge load

reinforcement, especially structures near coastal areas and in marine environments. Many bridges have been demolished due to heavy corrosion at ages of just 20–30 years and, in some cases, the maintenance costs far outweighed the initial construction costs (Tanaka et al. 2001).

Corrosion of steel reinforcement in concrete is due to an electrochemical process and must be taken into account in design and is dependent on the material quality

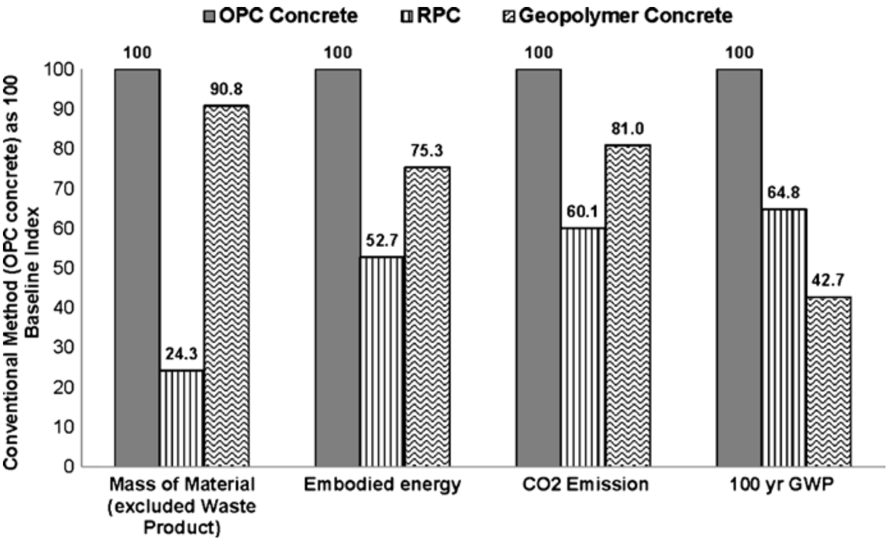

Fig. 5.8 EIC comparison for 1.5 m high retaining wall

and the environmental conditions. The high alkalinity nature of concrete passivates the reinforcement and protects it from corrosion (Tuutti 1982). However, if the concrete is permeable to the extent that carbonation reaches the concrete in contact with the steel or soluble chlorides can penetrate right up to the steel reinforcement, the reinforcement will be depassivated. Pitting corrosion and/or uniform surface corrosion will subsequently initiate.

The concept of chloride attack due to chloride ions permeating into reinforced concrete is illustrated in Fig. 5.9. The matrix of conventional concrete is analogous to that of a sponge (Fig. 5.9a) where the air voids, micro-pores, gel-pores and capillaries are inter-connected to each another. These micro-pores and gel water, which are generally formed in the concrete matrix, serve as routes for the movement of chloride ions. The pore structure in concrete depends on the type of concrete, mix proportion, type of formwork, placing technique, curing method, heat of hydration and material quality.

Unlike conventional concrete, RPC has a densely packed microstructure (Fig. 5.9b) in which the water/binder ratio is lowered to below the hydration limit (Water to Binder (W/B) ratio of 0.16 or less). Thus air voids are significantly reduced and are discontinuous in the matrix. Table 5.1 shows the chloride diffusion coefficient (D_c) of RPC is about an order less than for conventional concrete. For geopolymer concrete, the binder has densely packed microstructure with discontinuous air voids and micro pores. Only relatively few chloride diffusion studies have been published to-date for geopolymer concrete. Muntingh (2006) found that the D_c of geopolymer concrete is lower than 3×10^{-9} mm^2/s, i.e. more than 300 times lower than that of Portland cement concrete. Therefore in the presence of chloride ions at the surface of the concrete, the amount of time needed for the chloride ions to diffuse through geopolymer concrete and RPC's cover and initiate depassivation of the steel increases

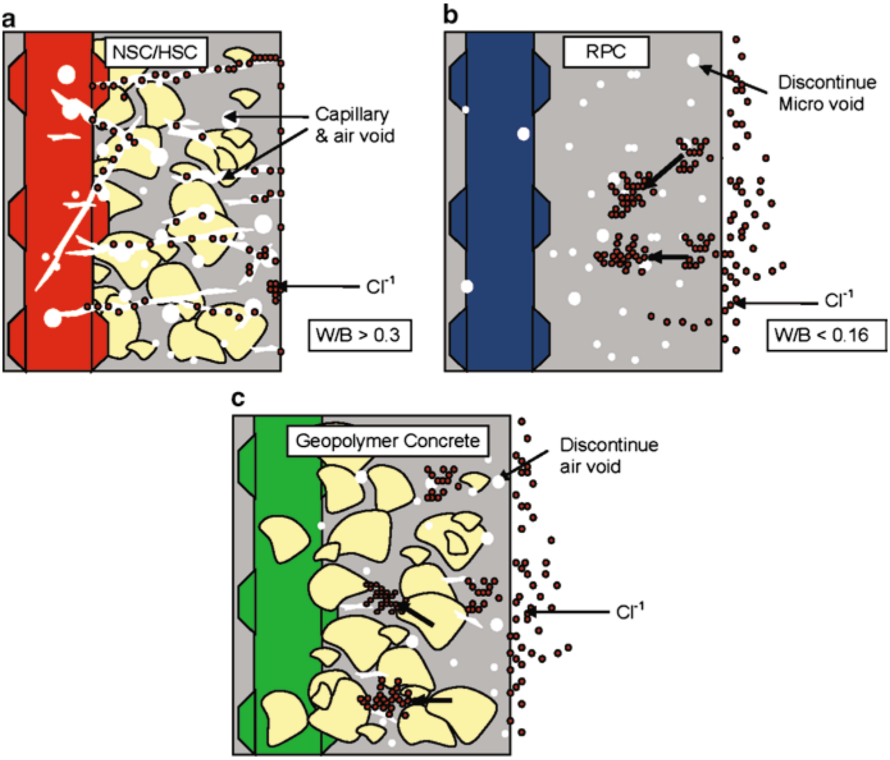

Fig. 5.9 Comparison of concrete matrix of (**a**) normal and high strength Portland cement concrete, (**b**) RPC, and (**c**) Geopolymer concrete

Table 5.5 Durability calculation in marine environment (for air-borne salt)

	HSC		Geopolymer concrete	RPC
Concrete cover, X (mm)	50	200	50	50
Airborne chloride concentration, C_s (kg/m^3)	6.4	6.4	6.4	6.4
Chloride threshold concentration, C_{ox} (kg/m^3)	1.2	1.2	1.2	1.2
Chloride diffusion coefficient, D_c (mm^2/s)	3×10^{-6}	3×10^{-6}	3×10^{-9}	6.7×10^{-8}
Time (years), *t*	**7.6**	**120**	**>1,000**	**340**
Time/120 years design life (%)	6.33	100	>1,000	283

dramatically. Of course, this assumption is only valid provided the geopolymer concrete and RPC is uncracked.

Taking the 40 m long bridge example discussed in the previous section, Voo and Foster (2010) provided a comparison between the durability of high strength concrete and RPC. The duration needed for chloride ions to diffuse through the concrete to initiate the reinforcement corrosion was undertaken using Fick's second law of diffusion. In this paper, diffusion time for geopolymer concrete is also assessed and the results are presented in Table 5.5. For a 50 mm concrete cover, corrosion initiation of the reinforcing steel in a Grade 60 high strength concrete girder will occur after just after 7.6 years, on the other hand, a depassivation in RPC girder will not start for 340 years. More interestingly, for geopolymer concrete, depassivation will not theoretically begin for at least a 1,000 years if the concrete is uncracked (such as may occur in members in compression or in prestressed construction). This may partly explain why the ancient buildings built using geopolymer concrete technology such as the Roman's Coliseum and Pantheon are still standing even after 2,000 years! To meet a 120 year no maintenance criteria, a cover, in theory, of 200 mm would be required for high strength concrete girder. Thus without regular maintenance, or passive or active corrosion protection systems, many concrete structures in marine environments fail at an early age. In comparison, geopolymer concrete and RPC structures have potential for significant savings in maintenance costs and a longer working life leading to more sustainable solutions.

5.5 Conclusions

An overview is presented on the sustainability design approach. This design approach not only accounts for the limit states design but also takes into consideration the environmental impact and durability of the designed structures. Two examples of environmental impact calculations (EIC) for typical structures is provided for conventional Portland cement concrete, geopolymer concrete and RPC solutions. The EIC results show that geopolymer concrete and RPC structures are able to give immediate savings in terms of primary material consumption, embodied energy, CO_2 emissions and reduce the global warming potential (GWP). With regard to durability design, geopolymer concrete and RPC structures are shown to be superior over conventional Portland cement concrete. Geopolymer concrete and RPC structures have potentially significantly longer service life and design life without impacting on the integrity or safety of the structure. The geopolymer concrete and RPC technologies are confirmed to be greener construction materials and support the vision of a sustainable construction future.

The authors are of the opinion that in the future, geopolymer concrete and RPC technologies will contribute significantly to the realisation of sustainable development. These technologies will lower the impact on the environment while providing efficient structural performance and provide a minimum total life-cycle cost solution. In summary, geopolymer concrete and RPC technologies can provide the following benefits:

- Encourage the use of recycled materials (such as silica fume, fly ash and grounded granulated blast furnace slag);
- Prolong the service and design life of structures (and thus delay the need of new replacement that requires consumption of new materials, new budgeting costs and construction interruptions to the public);

- Minimum maintenance due to superior durability (providing immediate savings in costs for repair and rehabilitation);
- Reduction in overall CO_2 emissions, embodied energy and GWP through savings in material consumption for RPC and total elimination of the use of Portland cement for geopolymer concrete; and
- Saving in the total life-cycle cost, which helps to relieve the future national economies.

It is also recommended that objective measures using embodied energy and 100-year global warming potential (GWP) are introduced to enable designers to evaluate, quantify and compare relative environmental implications of their designs.

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