HOW TO DESIGN DURABLE CONCRETE MIX FOR SUSTAINABILITY?

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ABSTRACT

In order to achieve the sustainability of social development, low carbon emission has played more and more important role. In this complex world scenario, infrastructure regeneration and rehabilitation; cement and concrete materials have an undeniable part to play in enhancing the quality of human life. If we are to avoid unredeemable environmental degradation globally, sustainable development of the cement and concrete industry has to be the foundation for all construction activity in the next millennium. The durability of cement and concrete materials is closely related to low carbon emission and energy saving. High performance and high durable concrete materials can contribute to the saving of raw materials, reducing of cement usage as well as low maintenance for long life. In order to achieve the objective of low carbon emission for ready mix concrete products, the design of concrete mix should be reconsidered. In this paper, the principles of ready mix concrete design has been discussed based on the durability requirements according to the new concrete Standard SS EN206-1. In every step of the design, the requirement of low carbon emission and green materials has been considered. Examples of design procedures are also illustrated in this paper for easy reference.

Keywords: *Concrete Specification; Design; Durability; Sustainability; SS544-1,*

1. INTRODUCTION

Concrete material is one of the important construction materials with the highest volume in the construction industry today. To achieve low carbon emission for concrete industry, ready mix concrete should play very important role. To build low carbon emission building, low carbon and energy saving concrete must be available (Swamy, 2000).

Most of Singapore Standards (SS) for civil engineering are based on British Standards (BS) and BS has been integrated into European Standards. Since 2006, Spring Singapore and Building and Construction Authority (BCA) have organized experts in concrete industry to review and draft the new Singapore Concrete Standards SS EN 206-1 (Spring Singapore, 2009) and complementary Standards SS 544-1 (Spring Singapore, 2009a) and SS 544-2 (Spring Singapore, 2009b). These new standards were officially published in 2009.

In SS 544-1: Method of specifying and guidance for the specifier, the basic and additional requirements for different concrete mix are listed. In this paper, different kinds of concrete will be introduced according to SS 544-1. The design procedure and methods for different concretes will be discussed. The consideration of low carbon and green requirements has been incorporated into the mix design method. An example is used to illustrate the every step of the concrete design.

2. CONCRETE SPECIFICATION BY SS 544-1

The SS 544-1 offers five approaches to the specification of concrete (Spring Singapore, 2009):

a. Designated concretes: For many common applications, the simplest approach is to specify a designated concrete. Designated concretes were developed to make the specification of designed concretes simpler, complete and more reliable.
b. Designed concretes: Designed concretes are suitable for almost all applications. They may be

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used as an alternative to designated concrete and should be used where the requirements are outside of those covered by designated concretes.

c. Prescribed concretes: This approach allows the specifier to prescribe the exact composition and constituents of the concrete. It is not permitted to include requirements on concrete strength, and so this option has only limited applicability.

d. Standardised prescribed concretes: Standardised prescribed concretes are applicable for housing and similar construction where concrete is site-batched on a small site or obtained from a ready-mixed concrete producer who does not have accredited third-party certification.

e. Proprietary concretes: This approach is appropriate where it is required that the concrete achieves a specific performance, using defined test methods.

Generally, in Singapore, most concrete supplied in the market is designed concrete. For designed concrete, the specification requirements according to SS 544-1 are listed as below (SS 544-1, 2009):

Basic requirements:

a. a requirement to conform to SS 544-2
b. the compressive strength class (Table 1)
c. the limiting values of composition, e.g. maximum w/*c* ratio, minimum cement content or the DC-class where appropriate (Table 2)
d. where the DC-class has not been specified, the permitted cements and combinatio (Table 3)
e. the maximum aggregate size where a value other than 20 mm is required
f. the chloride class where a class other than Cl *0.4* is required
g. for lightweight concrete, the density class or target density
h. for heavyweight concrete, the target density
i. the class of consistence or, in special cases, a target value for consistence (Table 4).

Table 1: Compressive Strength Classes for Normal-Weight and Heavy-Weight Concrete

Compressive Strength Class	Minimum Characteristic Cylinder Strength N/mm^2	Minimum Characteristic Cube Strength N/mm^2
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C25/30	25	30
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

Additional requirements:

a. Special types or classes of aggregate, e.g. for wear resistance or freeze-thaw resistance
b. Where the use of coarse RA is deemed acceptable, a statement that coarse RA is permitted and a requirement for the RA to conform to SS 544-2 : 2009, 4.3
c. Restrictions on the use of certain aggregates
d. Generic type and dosage of fibres
e. Characteristics required to resist freeze-thaw attack, e.g. air content
f. Requirements for the temperature of the fresh concrete, where different from the lower limit in SS EN 206-1 : 2009, 5.2.8 or the upper limit in SS 544-2 : 2009, 5.4
g. Strength development
h. Heat development during hydration
i. Retarded stiffening
j. Resistance to water penetration
k. Resistance to abrasion
l. Tensile splitting strength
m. Other technical requirements, e.g. requirements related to the achievement of a particular finish or special method of placing
n. Any “concerning” effects together with the tests to be applied and the acceptability criteria

Table 2: Limiting Values of Composition and Properties for Concrete where a DC-Class is Specified

DC-Class	Max, w/c Ratio	Min. Cement Content for 20mm Aggregate	Cement and Combination Types
DC-1A)	-	-	All
DC-2	0.55	320	IIB-V+SR, IIIA+SR, IIIB+SR, IVB-V
	0.50	340	CEM I, SRPC, IIA-D, IIA-Q, IIA-S, IIA-V, IIB-S, IIB-V, IIIA, IIIB
	0.45	360	IIA-L or LL≥42.5
	0.40	380	IIA-L or LL 32.5
DC2z	0.55	320	All
DC-3	0.50	340	IIIB+SR
	0.45	360	IVB-V
	0.40	380	IIB-V+SR, IIIA+SR, SRPC
DC-3z	0.50	340	All
DC-4	0.45	360	IIIB+SR
	0.40	380	IVB-V
	0.35	380	IIB-V+SR, IIIA+SR,SRPC
DC-4z	0.45	360	All
DC-4m	0.45	360	IIIB+SR

A) If the concrete is reinforced or contains embedded metal, the min concrete quality for 20mm maximum aggregate size is C25/30, 0.65, 260

Table 3: Maximum Chloride Content of Concrete

Concrete Use	Chloride Content Class[a]	Maximum CI Content by Mass of Cement[b]
Not containing steel reinforcement or other embedded metal with the exception of corrosion-resisting lifting devices	Cl 1.0	1.0 %
Containing steel reinforcement or other embedded metal	Cl 0.20	0.20%
	Cl 0.40	0.40 %
Containing prestressing steel reinforcement	Cl 0.10	0.10 %
	Cl 0.20	0.20%

[a] For a specific concrete use, the class to be applied depends upon the provisions valid in the place of use of the concrete.
[b] Where type II additions are used and are taken into account for the cement content, the chloride content is expressed as the percentage chloride ion by mass of cement plus total mass of additions that are taken into account.

Table 4: Slump Class

Class	Slump in mm
S1	10 to 40
S2	50 to 90
S3	100 to 150
S4	160 to 210
S5	≥ 220

3. Low Carbon Emission Consideration for Specification

As we know, carbon emission of concrete mainly comes from cement production. One ton of carbon dioxide will be released for production of one ton of cement. There are 3 main sources of carbon emission from cement production as shown in Figure 1.

a. Energy supplied to clinker kiln : 50% (300-450kg CO_2 per ton of cement)

b. Decomposition of limestone : 50% (450kg CO_2 per ton of cement)

c. Electricity and transportation : very low percentage

Therefore, for the design of low carbon concrete the first choice is to use the minimum cement content to produce durable and high performance concrete mix to meet the requirements of structure design. Choice of suitable raw materials, including concrete admixture, is the second consideration. It is followed by usage of industry and construction waste materials. Design of durable and high performance is essential for green concrete.

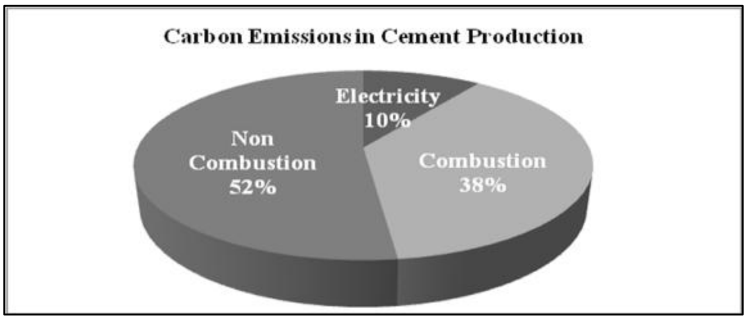

Figure 1: Carbon Emissions in Cement Production

3.1. *DESIGN OF HIGH PERFORMANCE CONCRETE TO REPLACE NORMAL CONCRETE*

Compared to normal concrete, the use of high strength concrete can reduce the structure size, so that not only the volume of concrete materials, energy consumption and manpower can be reduced; but also the usable area of the building can be increased. It is illustrated in Table 5 where, for the same loading capacity, the columns with high performance concrete can save up to 55% of concrete volume or 18% cement usage. Although the cement content per m^3 concrete is increased, the following effectiveness can be achieved:

a. Increasing of compressive strength of concrete can reduce concrete volume

b. The weight of structure is reduced, so that the size of foundations can be reduced.

c. The design for earthquakes can be reduced.

3.2. *USE SUPPLEMENTARY CEMENTING MATERIALS*

There are 27 types of cement in the new cement standards SS EN 197. With the exceptions of of CEM I and SRPC, all other cements contain supplementary cementing materials. In SS 544-2, cements are grouped into 7 categories, as shown in Table 6.

Table 7 shows the comparison of energy consumption of ordinary cement with supplementary cementing materials. To produce 1 ton of cement with 65% slag powder only needs 0.5 ton raw materials, and 1,500-1,600MJ of energy. Every ton of cement can save at least 6,000 MJ energy.

To produce one ton cement, 1.0-1.2 ton of CO_2 will be released. Table 8 provides a comparison of concrete with supplementary cementing materials. It can be seen that cement with 30% fly ash can reduce carbon emission by 20%, while cement with 50% GGBS can reduce Carbon emission by 43-50%.

Table 5: Comparison between High Performance Concrete and Normal Concrete

Type of Concrete	Normal (28 MPa)	High Performance (62 MPa)
Total binding materials (kg/m^3)	330	510
Mineral Addition (kg/m^3)	65 fly ash	24 silica fume
OPC (kg/m^3)	260	490
Column size(mm)	900 X 900	600 X 600
Concrete volume(m^3)	3.8	1.7
Volume reduction (%)	-	55
Cement reduction (kg)	1000	820
Cement reduction (%)	-	18

Table 6: Categories of Cements

CEM I	Portland Cement
SRPC	Sulfate-resisting Portland cement
IIA	PC with 6 to 20% other material
IIB-V	PC with 21 to 35% fly ash
IIIA	PC with 36 to 65% ggbs
IIIB	PC with 66 to 80% ggbs
IVB-V	PC with 36 to 55% fly ash

Table 7: Comparison of Energy Consumption

Energy Consumption		
Cement	7,500	MJ/ton
Fly Ash	150-400	MJ/ton
Slag	700-1,000	MJ/ton
CO_2 emission		
Cement	1.0-1.2	Ton/ton clinker

In conclusion, for the design of low carbon concrete, the principles for choosing cement should be as below.

a. Avoid to only use Ordinary Portland Cement
b. For normal construction, to use II B-V or III A cement (Tables 2 and 7)
c. For underground or marine construction, to use IV B-V or III B cement.

3.3. USE RECYCLED AGGREGATE TO REPLACE NATURAL AGGREGATE

Worldwide concrete industry faces the problem of shortage of aggregate resources. Looking for new sources of aggregate for concrete production started decades ago.

There are various studies on usage of sea sand, recycled concrete aggregate, mining tail and manufactured aggregate, etc. How to effectively use all available aggregate for concrete production is very important, especially for Singapore, which is a small country without any natural resource of aggregate. Compared to the old Singapore Standard on aggregate SS 31, the new Singapore Standard SS EN 12620 covers a wider range of aggregates, including natural aggregates, recycled aggregate as well as industry by-products. Complementary Singapore Standards for concrete SS 544-2 provides the definition and requirements for recycled aggregate.

Table 8: Comparison of carbon emission

Carbon emission ($kgCO_2/m^3$)			**Comparison to Normal concrete**	
Normal concrete	**30% fly ash concrete**	**50% slag concrete**	**30% fly ash concrete**	**50% slag concrete**
208	161	104	78%	50%
217	174	109	80%	50%
291	233	155	80%	53%
310	252	170	81%	55%
342	281	196	82%	57%

The definition of recycled aggregate in SS EN 206-1, Clause 3.0:

- Manufactured aggregate : Aggregate of mineral origin resulting from an industrial process involving thermal or other modification.
- Recycled aggregate : Aggregate resulting from the processing of inorganic material previously used in construction

The definition in SS 544-1, Clause 3.1:

- Recycled aggregate (RA) : Aggregate resulting from the reprocessing of inorganic material previously used in construction.

- Recycled concrete aggregate (RCA) : Recycled aggregate principally comprising crushed concrete.

The definition of recovered aggregate in SS EN 206-1, Clause 5.2.3.3:

- Recovered aggregate : Aggregate recovered from wash water or fresh concrete may be used as aggregate for concrete.

SS 544-2 specified the quality requirements of recycled aggregate as shown in Table 9.

SS 544-2 limits the usage of recycled coarse aggregate only for the concrete as listed in Table 10.

Clause 6.2.2 of SS 544-2 limits the usage of recycled aggregate: Where coarse RA or RCA is to be used in designated concretes *RC20/25* to RC40/50, its proportion shall be not more than a mass fraction of 20 % of coarse aggregate except where the specification permits higher proportions to be used. RA or RCA shall not be used in any of the FND or PAV designated concretes nor in designated concrete RC50XF.

In SS EN206-1, undivided recovered aggregate shall not be added in quantities greater than 5 % of the total aggregate. Where the quantities of the recovered aggregates is greater than 5 % of the total aggregate, they shall be of the same type as the primary aggregate and shall be divided into separate coarse and fine fractions and conform to SS EN 12620.

3.4. *USE OF CONCRETE ADMIXTURE*

Concrete properties can be modified by concrete admixtures. By using a concrete admixture, high performance durable concrete can be designed with low cement content, good workability, so that saving of raw materials, carbon emission, manpower and energy can be achieved. Table 10 shows the saving of cement content by using of concrete admixture.

In summary, for design of low carbon emission concrete the following points shall be considered:

- Use supplementary cementing materials to replace OPC, for normal construction, CEM II B-V or III A cement should be used, while for underground and marine construction, CEM IV B-V or III B cement should be used
- Use of concrete admixture
- Use of recycled aggregate to replace natural aggregate
- Avoid overdesign.

Table 9: Requirements for Coarse RCA and Coarse RA

Type	**Requirement A)**					
	Max Masonry Content	**Max Fines**	**Max light-Weight Material B)**	**Max Asphalt**	**Max other Foreign Material e.g. glass, plastics, metals**	**Max Acid- Soluble Sulfate (SO_3)**
RCA A)C)	5	5	0.5	5.0	1.0	1.0
RA	100	3	1.0	10.0	1.0	- D)

A) Where the material to be used is obtained by crushing hardened concrete of known composition that has not been in use, e.g. surplus precast units or returned fresh concrete, and not contaminated during storage and processing, the only requirements are those for grading and maximum fines.
B) Material with a density less than 1000 kg/m^3.
C) The provisions for coarse RCA may be applied to mixtures of natural coarse aggregates blended with the listed constituents.
D) The appropriate limit and test method needs to be determined on a case-by-case basis.

Table 10: Limit of Recycled Coarse Aggregate for Concrete

Type of Aggregate	**Limitations on use**	
	Maximum strength class[A)]	**Exposure classes [B)]**
RCA	C40/50	XO, XC1, XC2, XC3, XC4, XF1, DC-1

[A)] Material obtained by crushing hardened concrete of known composition that has not been in use and not contaminated during storage and processing may be used in any strength class.
[B)] These aggregates may be used in other exposure classes provided it has been demonstrated that the resulting concrete is suitable for the intended environment, e.g. freeze-thaw resisting, sulfate-resisting.

Table 11: Use of Concrete Admixture to Reduce Cement Content

Water Reducing Rate (l/m^3)	**Water Reducing Rate (%)**	**Cement Reducing (kg/m^3)(@0.55 w/c)**	**Cement Reducing (kg/m^3)(@ 0.40 w/c)**
10	5.6	18	25
15	8.3	27	37
20	11.1	36	50
25	13.9	45	62
30	16.7	54	75

4. DESIGN PROCEDURE OF LOW CARBON CONCRETE

4.1. DESIGN PROCEDURE ACCORDING TO SS 544-1

The design procedure for specifying concrete mix recommended by SS 544-1 is explained (Harrison and Brooker, 2005) as below:

- Step 1: Using Table A.1 in SS 544-1 to identify relevant exposure classes (Figure 3). If an aggressive chemical class is included, then go to Step 2. If not, then go to Step 10.
- Step 2: Using Table A.2 to classify ground conditions.
- Step 3: Using Table A.3 to select structural performance level.
- Step 4: Using Table A.4 to select DC-Class and number of APMs.
- Step 5: Are APMs recommended? If yes, go to Step 6, if no, go to step 10.
- Step 6: Are starred or double-Starred classes available? If yes, go to Step 4. If no, go to step 7.
- Step 7: Using table A.5 to select APMs
- Step 8: Is APM 1 included? If yes, go to Step 9, if no, go to step 10.
- Step 9: Increase DC-Class by 1 class for each application of APM1.
- Step 10: From Scheme design, note intended working life, compressive strength class, cover and margin (Δc).
- Step 11: Consider and note other factors to be considered.
- Step 12: Using Table A.10 to A.16 for each of the relevant exposure classes, note the nominal cover, limiting values and properties.
- Step 13: Select the limiting values to be used in the specification.
- Step 14: Is the resulting strength class or nominal cover different from that noted in Step 10? Are APMs other than APM1 required. If yes, go to step 15. If no, go to step 16.
- Step 15: Take account of the changes in the design.
- Step 16: Specify the basic requirement using clause 4.3.2 in SS 544-2 as a checklist.

- Step 17: Specify any additional requirements and provisions using clause 4.3.3 as a checklist.
- Step 18: Add, where relevant, information from the specifier using clause 5.1 as a checklist.
- Step 19: Where required, list information required from the producer using clause 5.2 as a checklist.

4.2. EXAMPLE OF THE DESIGN PROCEDURE

This example follows the steps illustrated on the above. Suspended reinforced concrete internal office slab that will be carpeted. The concrete will be pumped, compacted with a beam vibrator and finished with a bull-float. The columns of this building require C32/40 concrete. As the slab is carpeted, there are no abrasion considerations. From Figure 2, the only relevant exposure class is XC1. For the determination of exposure class, Figure 2 can be referred to.

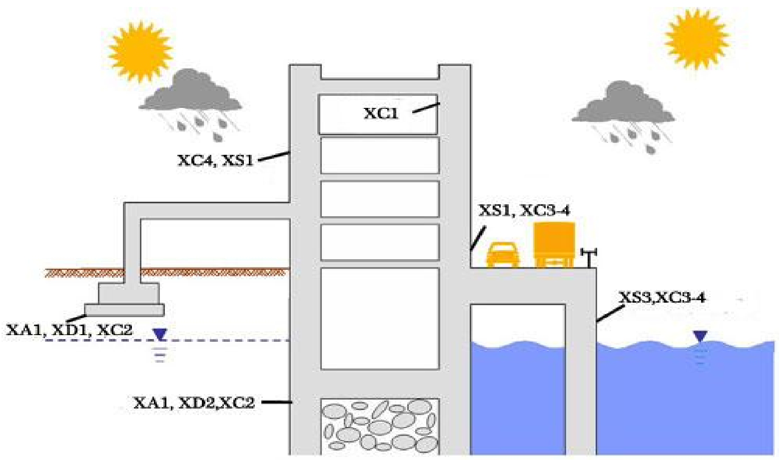

Figure 2: Exposure Class

As there are no aggressive chemical classes, refer step 10. As this is a normal building structure, EN 1990: Basis of design, recommends an intended working life of (at least) 50 years. The scheme design was done to EN 1990 and this assumed a C25/30 concrete with 25 mm nominal cover. There is also a need to select the margin and express the nominal cover as a minimum cover plus the margin (Δc). EN 1992–1: Eurocode 2: Design of concrete structures - Part 1: general rules and rules for buildings gives guidance on the selection of the margin Δc. It indicates that the value should be a function of the level of control on site. However the consequence of low cover should also be a factor in its selection and as this is an internal environment with no real durability concerns, a value of 5 mm for Δc with normal levels of workmanship is appropriate. A value of 5 mm for Δc is selected. The nominal cover from the scheme design is therefore (20 + 5) mm.

Refer step 11 the specifier should select the maximum aggregate size and the consistence class (or target value). The specifier selects a maximum aggregate size of 20 mm. The concrete is reinforced and the specifier decides to follow the guidance in clause 4.2A in SS 544-1 for the chloride class, namely Cl 0.4. The specifier selects slump class S3 as being suitable for the pumped concrete. As the concrete will be ready-mixed, the specifier decides that accredited third party certification is required. Refer to Table A.4 in SS 544-1, the limiting values and properties of concrete and the nominal cover to reinforcement for the XC1 exposure is nominal cover for durability is (15 + 5) mm and concrete C20/25, 0.70, 240 (from Table 12 for maximum aggregate size of 20 mm) and all cements/combinations in Table A.6.

There are no other exposure classes to consider. Refer step 13 for a nominal cover of (15 + 5) mm, the limiting values and properties of the concrete are C20/25, 0.70, 240, 20 mm maximum aggregate size and any cement/combination. Cement or combination types IIIB and IVB are normally specified for situations requiring high resistance to chlorides, sulphates or other aggressive chemicals. They also tend to have low rates of strength development in thin sections. Because the exposure classes do not include XD, XS or aggressive chemicals, cement/combination types IIIB and IVB were discarded at this stage of the process. As SRPC is also a special cement used for producing sulphate-resisting concrete, it is also discarded.

Refer step 14. There are differences between the durability design and the preliminary scheme design. Then refer step 15. The requirements are less onerous than those given in the scheme design, i.e. the strength class is down from C25/30 to C20/25 and the nominal cover is down from 25 mm to 20 mm. The designer then has the choice of leaving the scheme design unchanged or seeing if a more efficient design is possible. In this case, a check on the structural design showed that both the cover and concrete strength class could be reduced without material change to member sizes or reinforcement quantities. Hence the reduced cover and concrete strength are adopted.

Refer step 16. Basic specification requirements:

a) The concrete shall conform to SS 544–2 and SS EN 206–1

b) Compressive strength class: C20/25

c) Maximum w/c ratio: 0.70; minimum cement/combination content: 240 kg/m3

d) Cement or combination types I, II, IIIA from SS 544–2: 2002, Table 1

e) Maximum aggregate size: 20 mm

f) Chloride class: Cl 0.40

g) do not apply

h) do not apply

i) Consistence class: S3

Table 12: Durability Recommendations for Reinforced or Pre-stressed Elements with an Intended Working Life of At Least 50 Years (Extracted from Table A.4, SS-544-1)

Nominal Cover B) mm	**Compressive Strength Class Where Recommended, Maximum Water-Cement Ratio and Minimum Cement or Combination Content for Normal-Weight Concrete C) with 20 mm maximum aggregate size)**								**Cement/ Combination Types**
	$15 + \Delta c$	$20 + \Delta c$	$25 + \Delta c$	$30 + \Delta c$	$35 + \Delta c$	$40 + \Delta c$	$45 + \Delta c$	$50 + \Delta c$	
Corrosion induced by Carbonation (XC Exposure Classes)									
XC1	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	*C20/25* 0.70 240	All in Table A.6
XC2	-	-	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	All in Table A.6
XC3/4	-	*C40/50* 0.45 340	*C30/37* 0.55 300	*C28/35* 0.60 280	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	All in Table A.6 except IVB-V IVB-V
	-	-	*C40/50* 0.45 340	*C30/37* 0.55 300	*C28/35* 0.60 280	*C25/30* 0.65 260	*C25/30* 0.65 260	*C25/30* 0.65 260	

Refer step 17.

Additional requirements (see Step 11):

The producer shall operate an accredited quality system meeting the requirements of SS ISO 9001.

When tested in accordance with BS EN 1367–4, the aggregate drying shrinkage shall be not more than 0.075%. The SS EN 12620 Los Angeles category of the coarse aggregate shall not be greater than LA40.

Go to step 18.

Information from the specifier to producer: The concrete will be pumped, compacted with a beam vibrator and finished with a bull-float. Go to step 19.

Information required from the concrete producer: The specifier identifies that items f) and g) are relevant and therefore requests this information as follows:

Following information are supplied prior to delivery:

a. If RCA or RA is to be used, the type of material and the proportion to be used.

b. Where RCA or RA is not classed as highly reactive with respect to alkali-silica reaction, the proof on which the lower classification was based.

5. SUMMARY

- Design of concrete specification must follow the new Singapore Standards SS EN 206-1, SS544-1 and SS 544-2
- To design and produce high performance and durable concrete is meaningful for low carbon emission and sustainability of concrete industry
- The design of concrete specification for low carbon and durable concrete can follow the principles as below
- Use supplementary cementing materials to replace OPC, for normal construction, CEM II B-V or III A cement should be used, while for underground and marine construction, CEM IV B-V or III B cement should be used
    - Use of concrete admixture
    - Use of recycled aggregate to replace natural aggregate
    - Avoid overdesign

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