4TH CHIAM TEONG TEE MEMORIAL LECTURE

THE PAST, PRESENT & FUTURE OF CONCRETE CONSTRUCTION

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ABSTRACT

Concrete has always been the major construction material since the historical past, at present and will continue into the future. This presentation covers the period from the first UK design code (CP 114, 1957) in UK to the current European design code (BS EN 1992-1-1: 2004) and their associated standards on concrete and its constituent materials. The 10th Professor Chin Fung Kee Memorial Lecture in 2000 on "Concrete: From 2000 psi to 80 MPa and Beyond" was delivered before the adoption of Eurocodes. This new system is based on performance approach, in place of the more prescriptive approach of the former UK system. Engineering education and practice have to meet the changes with updated knowledge to benefit from these advances in design, materials and construction. The main emphasis is on changes in concrete with new types of cement, addition, admixture and the diminishing stock of aggregates. Replacing the traditional reliance on past experience with innovative approaches in concrete technology based on acceptance of rational performance criteria leads to progress in the construction industry. The progressive advances over the past six decades provided by personal experience have transferred through the teaching, research and development of new concrete concepts in concrete technology to the construction industry. There is also an urgent need to look into the future direction for concrete and the associated challenges ahead with the expected global warming to achieve higher levels of strength, consistence and durability for a sustainable concrete construction industry.

Keywords: Concrete, cementitious materials, additions, admixtures, strength, consistence, durability, sustainability

1.0 INTRODUCTION

Concrete has always been the major construction material since the historical past, at present and will continue into the future. This presentation covers, the period from the first UK design code (CP 114, 1948, revised 1957) in UK to the current European design code (BS EN 1992, 2004) and their associated standards on concrete and its constituent materials. The 10th Professor Chin Fung Kee Memorial Lecture (Tam, 2000) on "Concrete: From 3000 psi to 80 MPa and Beyond" was delivered before the adoption of Eurocodes. This new system is based on performance approach, in place of the more prescriptive approach of the former UK system.

2.0 CONSTITUENT MATERIALS FOR CONCRETE

2.1 Cement

Concrete is a composite material consisting of cement, water and both fine and coarse aggregates in appropriate compositions to achieve adequate strength for structural safety, sufficient consistence (formerly workability) for ease of construction, and durability of a chosen intended design working life in its exposure environment during service.

The term cement as defined in BS EN 197-1 (2011) refers to 27 types of common cements and 7 types of sulfate resisting common cements. Formerly BS 12 (1978) had 2 types of Portland cements, (a) Ordinary Portland Cement, (OPC) and (b) Rapid Hardening Portland Cement, (RHPC). As most concrete construction projects preferred RHPC over OPC for faster rate of strength development, OPC become "Obsolete" Portland cement and was left out in the revised BS 12 (1991). Even though it is no longer produced, the term OPC remains in common use in specifications and publications.

With the change from individual specification for each type of Portland cements in UK to all types under a single standard (EN 197-1), designers and specifiers have to select and specify which of the 34 types is to be used for a specific application. Each type of common cement has its advantages and disadvantages in terms of both technical and cost implications. Engineering education and practice have to meet the changes with updated knowledge to make the most appropriate selection with understanding of the physical and chemical compositions of each type of cement. In addition, the use of additions and chemical admixtures and their effects on both fresh and hardened properties of concrete are important factors in the final specification of concrete for each specific application.

The role of supplementary cementitious materials (SCM/ additions) such as fly ash (FA), ground granulated blastfurnace slag (GGBS) and silica fume (SF) in relation to pozzolanic reactions needs to be appreciated. The secondary reaction becomes significant when the primary reaction of the cement (CEM I) with water has generated sufficient calcium hydroxide to activate the silicates in the SCM either as a blended cement (EN 197-1) or batched into the mixer, defined as combination in BS 8500-1 (2016). The SCMs are deemed to be by-products and hence of a much lower carbon footprint compared to cement clinker to achieve better sustainability for concrete.

The drive to lower carbon footprint in cement has led to the development of non-Portland cements, e.g. geopolymers. In UK a newly published document, Publicly Available Standard, PAS 8820 (2016) applies to all types of alkali-activated cementitious materials. Some examples of application of this new type of cement have been reported by Ball and Greet (2014) and Aldred *et al* (2015).

2.2 Water

Water is other necessary component in concrete. In urban centres potable water is suitable and available for use as both mixing and curing water for concrete. Where potable water is not available, there is a need for acceptance criteria and test methods to be adopted to ensure the water is suitable as mixing and curing of concrete. The former BS 3148 (1980) was useful as a guide but did not provide acceptance criteria. Currently BS EN 1008 (2002) is a specification for mixing water stating both test methods and conformity requirements. It includes the use water recovered from processes in the concrete industry, as mixing water for concrete to promote conservation of resources as well as avoidance of treatment before disposal.

2.3 Aggregates

Aggregates form the largest volume of constituents in concrete as a composite material. The combined grading of fine and coarse aggregates serves to form the particles in the matrix of cement paste (two phase concept). There are only limited changes compared to the former BS 882 (1992). The major difference is that BS 882 (1992) was limited to “aggregates from natural sources for concrete”. A minor change is in the maximum particle size for fine aggregate. BS EN 12620 (2010) changed the upper size of fine aggregate from 5 mm sieve to 4 mm sieve size. In the 1973 edition of BS 882 four grading zones were introduced. “The division into zones was based primarily on the percentage passing the 600 µm (No. 30 ASTM sieve) sieve. The main reason for this was that a large number of natural sands divide themselves at just that size, the gradings above and below being approximately uniform” (Neville, 2012). This was based on sands available in UK. “Little of these sands is now available for concrete-making, and a much less restrictive approach to grading is reflected in the requirements of BS 882: 1992" (Neville, 2012). Only an overall grading is required with three additional grading limits into coarse, medium and fine grading with overlapping ranges. Similar approach is adopted in BS EN 12620 (2002) Annex B (informative). Coarseness or fineness is based either on the percentage passing the 0.500 mm sieve (replacing former 0.600 mm sieve) or on the fineness modulus (adopted also by ASTM C33-18). Fineness modulus (FM) is calculated as the sum of cumulative percentages by mass retained on the following sieve (mm) expressed as a percentage, i.e.

$$FM = \sum\{(>4) + (>2) + (>1) + (>0.5) + (>0.25) + (>0.125)\}/100$$

Comparison of the former BS 882 and current BS EN 12620 and ASTM C33-18, on the coarseness or fineness requirements as shown below:

BS 882: 1992 - Percentage by mass passing sieve

Sieve size	Coarse	Medium	Fine
2.36 mm	60-100	65-100	80-100
1.18 mm	30-90	45-100	70-100
600 µm	15-54	25-80	55-100
300 µm	5-40	5-48	5-70

BS EN 12620: (2002) – Percentage passing 0.500 mm sieve

CP	MP	FP
5-45	30-70	55-100

BS EN 12620: (2002) – Fineness modulus

CF	MF	FF
4.0-2.4	2.8-1.5	2.1-0.6

ASTM C33-38 – FM: 2.3-3.1

It can be observed that a wide range of fine aggregate grading as indicated above can be used in concrete. Hence, actual usage can be developed by “initial tests” to meet specified performance often at an increased cost rather than technical limitations.

BS EN 12620 (2002) includes the use of recycled aggregates (RA) and recycled concrete aggregates (RCA). BS 8500-1 (2016) introduced separate definitions for RA from reprocessing of inorganic material previously used in construction and crushed concrete aggregate (CCA in place of RCA) which is principally comprising “aggregate obtained from crushed concrete”. “Coarse CCA and coarse RA conforming to BS 8500-2 may be used in designed concrete up a maximum strength class C40/50”. “Coarse CCA 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 in any strength class”. Such concrete elements may be from concrete test specimens for production conformity and precast elements that are rejected for production imperfection. “Although provisions for the use of fine CCA and fine RA are not given in BS 8500, this does not preclude their use where it is demonstrated that, due to the source of material significant quantities of deleterious materials are not present and their use has been specified or permitted”, e.g. permitted by project specification under “provisions valid in the place of use”. The new standard promotes the drive for sustainable concrete construction further considered in the section 5.5 on Sustainability.

2.4 Additions and Admixtures

The term addition in common usage often includes both mineral additions and chemical additions. BS EN 206 (2016) separates the two by their functions in concrete. Addition is used in concrete "to improve certain properties or to achieve special properties", e.g. Pozzolanic or latent hydraulic additions such as fly ash, ground granulated blastfurnace slag and silica fume. Admixture is used in concrete "to modify the properties of fresh and hardened concrete", e.g. plasticizing and retarding/accelerating set.

2.4.1 Additions

The most commonly used additions in concrete production are fly ash, ground granulated blastfurnace slag and silica. Fly ash is the by-product from the burning of pulverized coal. Fly ash for concrete is to be in accordance with BS EN 450-1 (2012), Fly ash for concrete – Part 1: Definition, specifications and conformity criteria. Ground granulated blastfurnace slag for use in concrete is to be in accordance with BS EN 15167-1 (2006), Ground granulated blastfurnace slag for use in concrete, mortar and grout – Part 1: Definitions, specifications and conformity criteria. Silica fume for concrete is to be in accordance with BS EN 13261-1 (2009), Silica fume for concrete – Part 1: Definitions, specifications and conformity criteria.

Use of additions in accordance with BS EN 206 (2016) has to meet conditions set in Annex A (normative) for "initial test". Suitability is established by any one of the concepts in Clause 5.2.5, "the k-value concept in 5.2.5.2.2 and the principles of the equivalent performance concepts (equivalent concrete performance concept (ECPC) in 5.2.5.2.3, and equivalent performance of combinations concept (EPCC) in 5.2.5.2.4. Further details on this topic are presented in a later section on concrete (3.4 Durability).

2.4.2 Admixtures

The earliest application of admixtures is air-entraining agents to meet freeze-thaw exposure which is not normally considered in tropical climate. In the 1960s, water-reducing and set-retarding admixture (1st generation, 1G) was lignosulfonates derived from leaching process in paper manufacture with reduced wood sugar. Superplasticizers in the 1980s are mainly naphthylene-formaldehyde-based (NSF type, 2G) specially produced in chemical plant. By the 1990s, polycarboxylate with long EO chains (PE type, 3G) is added. Since 2000s, PCE type (4G) provides engineered performance with enhancement of retardation or plasticizing functions. For PCE type, the absorption unit (carboxyl group in the main chain) and the steric repulsion unit (EO polymer in the side chain) can be independently engineered to vary the extent of set-retardation or the plasticizing function. Three types of applications are commonly available with superplasticizing admixture: (1) addition of plasticizer to increase consistence without change in strength, (2) reducing water content without change in consistence and at the same cement content to increase strength and (3) reduction is both water content and cement content but retaining the same water/cement ratio for strength and same consistence, resulting in cost saving for the same performance. Conformity testing of admixtures is in accordance with BS EN 934-2: 2001+A1:2012, Admixtures for concrete, mortar and grout – Part 2: Concrete admixtures – Definitions, requirements, conformity, marking and labelling, based on equal water/cement ratio, equal consistence and equal water/cement ratio with prescribed concretes.

With each new generation of set-retarding and plasticizing admixtures for a given water/cement ratio for strength, the required level of consistence is achieved with lower water content and hence also a lower cement content. Besides a saving in cost, there is the added reduction in embedded CO_2/m^3 of concrete. In recent years, further functions are introduced into chemical admixtures, e.g. shrinkage compensating (drying shrinkage) or shrinkage reducing (autogeneous shrinkage) and a move to introduce corrosion resistance function to the next generation of standardized chemical admixture. Former chemical admixture standard BS 5075 Parts 1 to 3 are replaced by BS EN 934 Parts 1 to 6 Admixtures for concrete, mortar and grout which cover definitions, requirements, conformity, smarking and labeling for admixtures, including grout for prestressing tendons and sprayed concrete.

2.5 Fibres

Two types of fibres are permitted in BS EN 206 (2016). These are steel fibres conforming to BS EN 14889-1 (2016) and polymer fibres conforming to BS EN 148890-2 (2016). Firbre content and homogeneity test methods and acceptance criteria for identity test are specified in Annex B (normative) of BS EN 206 (2016).

Polymer fibres have been used to mitigate plastic shrinkage cracking and steel fibres to replace conventional reinforcement gage in tunnel segment. Combination of these two types of fibres is becoming more common to achieve special performance, including fire rating besides crack control. Non-metallic fibre-reinforced polymer is a composite material made of a polymer matrix reinforced with fibres. "The fibres are usually glass (in fiberglass), carbon (in carbon fiber reinforced polymer), aramid, or basalt" (Wikipedia – Fibre-reinforced plastic, 08-Oct-19). Glass fibre reinforcement bars used in a foundation of a medical centre in France also meets the need to be electromagnetic interference-free (Revans, 2019).

3.0 CONCRETE

3.1 Historical Practice

Both in UK and USA, codified design and specification for concrete began around the mid-1930s. Over the next 8 decades, British codes for concrete evolved from the DSIR Code of 1934 to CP 114 (1948, revised in 1957) to CP 110 (1972) and the BS 8110: Part 1 (1985). This is currently replaced by BS EN 1992-1-1 (2004) and BS EN 206 (2016). Guidance on specification of concrete including durability first appeared in CP 110 (1972) as BS 5328 (1976) and expanded into 4 Parts in 1990 and 1991. Currently BS EN 206 (2016) has complementary UK standards (BS 8500-1 and 8500-2: 2016) for additional guidance. Similar complementary national standards based on UK guidance documents are published for guidance in Malaysia and Singapore. Only the specification of concrete will be presented in this lecture. The topics are compressive strength, consistence and durability.

3.2 Compressive Strength

Compressive strength of concrete can be correlated to other types of concrete strength and is the strength used in design.

In CP 114 (1957) it was based on nominal concrete mixes, e.g. 1:2:4 consisting of 112 lb of cement (= 50 kg bag), 2.5 cubic foot of fine aggregate and 5 cubic foot of coarse aggregate. The 28-day cube strength was to be 4000 psi (28 MPa) for preliminary test (trial mix/initial test) and 3000 psi (21 MPa) for works test (site samples). The working stress of concrete (in compression) of 1:2:4 concrete was 760 psi (5.3 MPa) in direct compression and 1000 psi (7 MPa) in bending based on elastic theory. The concept of characteristic strength was introduced in CP 110 (1972) with the change over from elastic design to limit state design with partial safety factor for load and for strength. The highest grade of strength is 60 MPa and remained the same in BS 8110 (1985). However, the modulus of elasticity was higher in CP 110 (1972) then in BS 8110 (1985), e.g. at the characteristic strength of 60 MPa, the static elastic modulus CP 110 (1972) was 36 GPa (mean) in the range of 30 to 42 GPa compared to the lower values in BS 8110 (1985) of 32 GPa (mean) in the range of 26 to 38 GPa. It is to be noted that in BS EN 1992-1-1 (2004) for the same characteristic strength of 60 MPa, the value is 37 GPa. The highest characteristic compressive strength in BS EN 1992-1-1 (2004) is C90/105 for which the elastic modulus is 44 GPa. It is a challenge to source for high strength coarse aggregate to achieve such high elastic modulus.

The design of concrete structures in BS EN 1992-1-1 (2004) adopts standard cylinder strength, but conformity may be based on either cylinder or cube compressive strength as stated in BS EN 206 (2016). For strength classes up to C55/67, standard (150 mm) cube compressive is around 1.25 times of standard (150 mm diameter by 300 mm length) cylinder compressive strength. From C60/75 to C100/115, a constant difference of 15 MPa is adopted. There is adequate experience and track record in the use of concrete strength class up to C55/67 but much less above it, it is prudent to test both type of standard specimens in the “initial test” stage (trial mix in current practice) to gain more confidence in the relationship, particular for countries where cube compressive strength is adopted for conformity. There is also the need to do the same as strength classes above C100/115 is expected in the future. The use of concrete with a higher strength class leads to smaller dimensions of structural elements which may lead to saving in cost but more so in materials for sustainability in concrete construction. Whether there is a reduction is carbon footprint will depend on the balance between the need of an increase in cement content for higher strength concrete versus the reduction in its volume to achieve the same structural requirements. Other benefits include less labour and time in casting and handling of concrete in production and transportation from plant to site. Possible cost saving in formwork and faster time for completion of project are added advantages.

In terms of reduction in concrete volume and hence cement used to achieve the objective of sustainability, the use of 100 mm cubes in lieu of 150 mm cubes for conformity testing should be promoted. The volume of concrete for one 150 mm cube (0.003375 m^3) is sufficient to make three 100 mm cube (0.001 m^3) with spare. The current practice of specifying standard cube strength to be determined with 150 mm cubes is likely due to the convenience of using one size to include concrete with 40 mm maximum aggregate size (e.g. pavement and unreinforced mass concrete applications). In most concrete construction, maximum aggregate size of 20 mm is specified and even 10 mm in cases of higher strength classes. The relation between specimen size and maximum aggregate size specified in BS 1881 (1952) prescribed a test cube not smaller than 4 in. (100 mm) when ¾ in. (20 mm) aggregate is used and 6 in. (150 mm) cubes with 1½ (40 mm) aggregates. ASTM C192 (1957) limits the ratio of the diameter of the cylinder to the maximum aggregate size to 3. “A value of between 3 and 4 is generally accepted as satisfactory” (Neville, 2012). According to BS EN 12504-1 (2000) the ratio of maximum aggregate size in the concrete to the diameter of the core has a significant influence on the measured strength, when it approaches a value greater than about 1:3. BS 8500-2 (2016) under conformity control for compressive strength it requires conformity to specified compressive strength class when determined using 100 mm cubes, "the minimum characteristic 100 mm cube strength shall be that prescribed for 150 mm cubes in BS 206 (2016)". The acceptance of 100 mm cubes for conformity has been in UK practice for many decades based on BS 1881 (1952). The relationship between compressive strength and water-cement ratio used in designed concrete given in Road Note No. 4 (1950) is based on 100 mm (4 in.) cubes. This is the basis which subsequent design of concrete methods adopt as the guide for selecting water-cement ratio for a given compressive strength.

According to size effect, smaller dimension specimens are expected to show higher measured strength. Neville (2012) reported limited published data in terms of cube compressive strength indicate the ratio of 100 mm (4 in.) cubes to that of 150 mm (6in.) cubes at about 1.04. Smaller size specimens also tend to result in higher variability in terms of standard deviation or coefficient of variation. However, the combined effect on characteristic strength is reduced. The value of the ratio = 1.05 was reported by Leung & Ho (1996) based on 8 projects with values of below 1.0 range from 4% to 22% with the mean for 17% for 349 individual ratios. Most of studies are limited in the size of the population for each strength level with each data based on the average of 3 specimens at each test age. Limited number of test data is unlikely to follow assumption of Gaussian distribution. Hence for small sample size the tendency is to have more results above the mean. The cube/cylinder strength ratio for concrete tends to be above unity. Daneti *et al* (2016) conducted a study with three strength levels (C32/40, C50/60 and C65/80) over a period of several months in a RMC plant used in actual production. A total of slightly over 100 batches for each strength level were produced and tested at the age of 28 days with moist curing from time of demoulding at age of one day. In all cases, the mean value of the ratio between 100 mm and 150 mm cubes is only 1.01 based on mean of individual batches or characteristic value. The average value for standard deviation of each cube size differs by less than 0.05 MPa. The distribution of the ratio for each of the 3 strength levels shows skew towards values above 1.0 with the percentage of value below 1.0 at 31% for C32/40 and C50/60 and even lower at 21% for C65/80. Based on this observation, it implies that for small number of batches, there is a high probability that the ratio will be above 1.0 as reported in other studies. It also supports the recommendation of BS 8500-1 (2016) to accept conformity based on the same as prescribed for 150 mm cubes in BS EN 206 (2016).

3.3 Consistence

Consistence is the new term for workability. Care should be taken to differentiate its usage from "consistency" which is the quality of always behaving or performing in a similar way. **As an example: quality assurance relies on the *consistency* of a concrete produced with the required *consistence* (e.g. slump) over the period of production.**

Normally, consistence in BS EN 206 (2004) may be specified in terms of different slump classes (S1 to S5, BS EN 12350-2:2009), compaction classes (C0 to C4, BS EN 12350-4:2009) and flow classes (F1 to F6, BS EN 12359-5 2009). Slump flow classes (SF1 to SF3, BS EN 12350-8 2010) apply to self-compacting (self-consolidating) concrete only. Although the final flow diameter and slump flow diameter are determined in both methods, "flow, F" and "slump flow, SF" are based on different test standards (cone size etc.). There is no direct correlation between consistence classes of one test method with those of another test method.

For SCC there are additional requirements. They include viscosity classes (VS1 and VS2 to BS EN 12350-8 2010) based on t_{500}, the time for flow to reach 500 mm in slump flow test and/or (VF1 and VF2 to BS EN 1250-9 2010) based on t_v, the time for flow through the V-funnel. The passing ability classes (PL1 and PL2 to BS EN 1259-10 2010) using the L-box and/or (PJ1 and PJ2 to BS EN 12350-12 2010) using the J-ring. In addition there is the sieve-segregation resistance classes (SR1 and SR2 to BS EN 12350-11 2010). The above types and ranges of consistence classes have been developed for specification needs. This is a great advancement from the requirement in CP114 for a given water/cement ratio: "The quantity of water used for reinforced concrete should be sufficient, but not more than sufficient, to produce a dense concrete of adequate workability for its purpose, which will surround and properly grip all the reinforcement. So far as possible, the workability of the concrete should be controlled by maintaining a water-cement ratio that is found to give a concrete which is just sufficiently wet to be placed and compacted without difficulty, with the means available". One should note that in those days, placing and compacting concrete were undertaken mostly by ladies known commonly as "Sam Sui Women" with reference to their home village in China. The women wearing typical red colour hair covering had only round reinforcement rods for compacting concrete. Yet with their dedication and passing to do things right, many structures built in those days are still standing. This is a far cry from to-day where SCC is used with no human effort needed for obtaining adequate compaction. Robots can now replace human in casting concrete within a factory for precast products! On the other hand, very low consistence concrete is needed for 3D printing method of constructing concrete structures. In Europe, some very interesting buildings and even a pedestrian bridge have been created with 3D printing techniques. Locally, an experimental prefabricated volumetric bathroom unit has been produced by this new technique in Singapore.

3.4 Durability

For this lecture only the provisions on exposure classes and requirements for composition of concrete are considered as they are developed over the past decades in specification requirements. Information on mechanisms and rate of attack, etc are available in many published documents and textbooks on concrete.

The durability exposure classes are generally given in a descriptive form. Similarly, requirements on concrete constituents and composition are also prescribed in descriptive terms. In CP 114 (1957) clause 210 highlighted the need for specified cover for reinforcement bars and concrete "should be dense, impermeable and of a quality suitable for the conditions of exposure involved". No specific details were provided, other than "nominal concrete mixers should not be used for structures exposed to sea water". Clause 352 covered the resistance to chemical attack mentioned chemical agents "such as vegetable oils and fats, sugar solutions and sulphates". "Increased resistance to some forms of chemical attack may be obtained by the use of high alumina cement or sulphate resisting cement or by the use of protective coatings".

CP 110 (1972) provided specific guidance on "minimum cement content" in Table 48 in which exposure were classified as "mild", "moderate", "severe" and "subject to salt for de-icing", with "the cement content should be sufficient to provide adequate workability with a low water/cement ratio so that the concrete can be completely compacted with the means available". Limits on maximum free water/cement ratio and minimum grade of concrete were introduced in BS 8110 (1985) for durability with also two new exposure conditions, "very severe" and "extreme". Details were provided in the new BS 5328 (1990-1991, in 4 parts). The current UK guidance is provided in Annex A (informative) of BS 8500-1: 2015+A1 (2016). Exposure classes and requirements on concrete includes types of cement and concrete cover in addition to minimum cement content and maximum free water/cement ratio as in previous UK standards. The provisions are in more details and included both intended design working life of 50 years and 100 years. Hence, they are preferred to the k-factor approach in clause 5.2.5.2 of BS EN 206 (2013) for intended design working life of 50 years covering only for fly ash and silica fume, but as informative value for ground granulated blastfurnace slag. The relevant standards provide full details for inclusion in specifications.

For sulfate in the ground, CP 110 indicated classes 1 to 5 based on concentration of sulfates with the requirements for minimum cement content and maximum free water/cement ratio. BS 5328 (1990-1991) refined class 4 into 4A and 4B and class 5 into 5A and 5B based on BRE Digest 363 (1991) which has been replaced with BRE Special Digest 1, 3rd Ed. (2005) Concrete in aggressive ground. The current UK guidance is provided in Annex A (informative) of BS 8500-1: 2015+A1 (2016) which provides much more guidance than the recommendations in Annex F (informative) of BS EN 206 (2013). In both Malaysia and Singapore, the UK approach in provisions for durability has been adopted historically from the colonial days. Even though the approach is semi-prescriptive, past performance and familiarity with the practice have served the needs adequately and should be followed until truly performance based design methods currently under development are codified. The two cases of carbonation in concrete and the diffusion coefficient for chloride ingress are likely to be the first to be introduced when the effects of various factors of the numerical equations are agreed upon. These include the service exposure environment factors such as temperature and relative humidity and factors in the resistance provided by concrete such as cement type and content, water/cement ratio and nominal design cover to reinforcement. All the factors will be in quantitative terms to replace of the current descriptive approach and semi-empirical prescribed values for concrete. In order to validate the recommended values for various factors, actual site exposure performance data are necessary to correlate them. It is in this regard that monitoring of existing concrete structures is very much limited in tropical climate. A few studies under controlled exposure in laboratory studies have been published. However, actual performance under service environment has not been monitored, particularly with adequate information on the insitu quality of the concrete cover and continuous recorded environmental data in tropical climate. This is an urgent issue as data from temperate climate will not adequately represent tropical climate. In the Foreword to the complimentary Singapore standard SS 544 (2019), guidance to cater for the higher tropical temperature when using recommended requirements for concrete in BS 8500 (2016) it is recommended to enhance the resistance of concrete. "In order to cater to the higher ambient temperatures in Singapore compared to UK, the recommendation is to consider the required concrete for at least one class higher than that based on exposure conditions in accordance with the requirements for UK exposure conditions (refer to Table A.3). The specifier should take into consideration the nature of the element, intended working life, its importance and the cost of maintenance and repair to select the same or higher performance concrete". Different elements in the same structure may be specified with different concrete to optimize cost-effectiveness. Limited data on the effect of tropical temperature over that in temperate regions have indicated significantly higher rate of carbonation and lower service life in marine exposure conditions (Otsuki *et al* 2006).

The above applied to chemical attack by sulfate from an external source which results in spalling from the surface in contact with the external source, e.g. soil or seawater. However, another type of sulfate attack comes from sulfate already within the concrete. This is referred to as internal sulfate attack (ISA) or by the delayed reaction product between sulfate (calcium sulfate sources, such as gypsum, intentionally added to Portland cement to regulate early hydration reactions to prevent flash setting, improve strength development, and reduce drying shrinkage) and the tricalcium aluminate in Portland cements to form ettringite (calcium sulfoaluminate ($3CaO•Al_2O_3$ $•3CaSO_4$ $•32H_2$ O). Ettringite formed at early ages is often referred to as “primary ettringite.” It is a necessary and beneficial component of Portland cement systems. Delayed ettringite formation (DEF) results in expansion and cracking of concrete associated with the delayed formation of ettringite which is a normal product of early cement hydration. This reaction ends when the sulfate concentration, needed for forming the ettringite, decreases below the limit. From this point the remaining C3A reacts with the already formed ettringite to monosulfate which in aqueous solution again form ettringite and tetracalcium aluminate hydrate. DEF is a result of high early temperatures (above 70 ^{O}C – 80 ^{O}C) in the concrete due to heat of hydration of cement which prevents the normal formation of ettringite, e.g. in thick sections. The occurrence of this form of sulfate attack in concrete was not fully recognized until late 1990's. It attracted much attention when accelerated curing of precast pretensioned railway sleeper in Europe showed map cracking after in service for several years. In those days, the accelerated curing regime had upper temperature maintained at 80 ^{O}C for several hours. Since the phenomenon was recognized, the upper temperature is now kept at 60 ^{O}C (possibly to avoid potential local hot spots within the curing environment). Up till the late 1990's some thick raft foundations and large pilecaps would have exceeded 70 ^{O}C for which DEF may have occurred during service. The highest temperature found in published literature was over 90 ^{O}C, incidentally shown in the publication by Cao (2000) on the construction of Jin Mao building. However, in such cases, it is likely that the volume of affected concrete is small and limited to the central core portion of the mass. Under compressive loading of the superstructure and the confinement effect of reinforcement cage in reinforced concrete, the resultant expansion due to DEF may not lead to any observed surface cracking during service.

In temperate regions, typical summer temperatures are around 20 ^{O}C and down to around 10 ^{O}C or lower in winter. For initial placing temperatures in these temperatures, maximum temperature developed in thick sections seldom exceeds 70 ^{O}C. Hence, the main concern is potential early thermal cracking. Nominal guidance on potential early thermal cracking suggests the temperature differential between the warmer interior and the cooler surface zone should be below 20 ^{O}C, e.g. BS 8110-2 (1985). For tropical climate average ambient temperature throughout the year is around 28 ^{O}C to 32 ^{O}C. Keeping maximum concrete temperature below 70 ^{O}C is possible at a high cost (either by means of pre-cooling of fresh concrete or by post-cooling of hardened concrete). Studies over the past two decades reported by Godart and Divet (2017) that cements containing SCM's meeting certain limits may have acceptable expansion without cracking due to potential DEF for peak hydration temperatures up to 75 ^{O}C, 80 ^{O}C or 85 ^{O}C.

Guidance on potential early thermal cracking given in BS 8110-2 (1985) Table 3.2 Estimated limiting temperature differential to avoid cracking is related to the statement: "Experience has shown that by limiting temperature differentials to 20 ^{O}C in gravel aggregate concrete, cracking can be avoided. This represents an equivalent restraint factor R of 0.36 and the corresponding values for concrete with other aggregate types are given in table 3.2". The limiting value at the same R = 0.36 for granite aggregate concrete is 27.7 ^{O}C and for limestone aggregate concrete 39.0 ^{O}C. Values of external restraint recorded in various structures given in Table 3.3 indicate for mass pour cast on blinding, e.g. raft foundation, R is 0.1 to 0.2, but for thin wall cast on to massive concrete base, R is 0.6 to 0.8 at base and 0.1 to 0.2 at top. Local experience has indicated that for raft foundations temperature differential up to 30 ^{O}C to 35 ^{O}C in raft foundations but a value of 12 ^{O}C to 14 ^{O}C has resulted in through cracks in thin walls cast on to massive concrete base due to high base restraint. Mitigating methods need to be developed to minimize this latter case in cut-and cover tunnel walls and tank walls for liquid containing tanks. Reducing boundary restraint is the mitigating approach, e.g. a low first lift with both ends free.

It is a common practice to rely on numerical analysis based on heat of hydration data from a "hot box" test to assess both issues. However this approach does not include the casting process which may take up over 10 hours or more in raft foundations. During this time, concrete placed earlier has already started to rise in temperature. Numerical analysis to include this stage is complicated by the need to change the thickness of concrete with time. In order to cater for this, a realistic mock-up method has been developed (Tam *et al*, 1997). It enables innovative concepts to be adopted when casting fresh concrete in multiple horizontal layers to ensure proper compaction, reducing cost by introducing the "ice-cream sandwich concept". Cost saving is achieved with only the interior zone with cooler concrete but both bottom and top outer zones with normal initial fresh concrete temperature. The concretes for different layers are designed for the same compressive strength but with optimization of the concrete designed not only of different initial placing temperatures but also include different types of cements and chemical admixtures of different functions (e.g. waterproofing, besides plasticizing and set-retarding). Using this approach, more than 2 million cubic metres of concrete for raft foundations have been satisfactorily placed over the past two decades in both Malaysia and Singapore. Similar concept of casting realistic simulation with a mockup has also been applied to casting of thick transfer girders, transfer plates and large diameter columns with high strength concrete of C60/75 and above.

For the case of thin wall cast on to massive base, the base restraint factor has been satisfactory reduced by casting the first lift of the wall with not exceeding 1 m. Preferably both ends of the wall are free or only one end of the wall may be continuous with existing wall of the same thickness but keeping the other end free. Limited local experience has shown that the free contraction of the top together with free end(s) of the new to be cast section of the wall is able to reduce the restraint factor sufficiently to avoid cracks being developed.

3.5 Sustainability

Constituents for concrete are increasing in demand for economic development in both developed and developing countries. In the future under-developed countries will also join such developments. Hence, it is critical that concrete construction should be based on a sustainable basis to extend the limited resources available for future generations. The main drive is to "Reduce, Reuse & Recycle", the three pillars of sustainability.

Reduce implies achieving the same result with less in terms of materials, energy (carbon footprint) and human effects. In concrete industry, minimizing the use of Portland cement with supplementing cementitious materials (fly ash, ggbs & silica fume) lowers the carbon footprint of concrete. Another challenge is to design concrete for the same performance requirements with lower cement content, e.g. high strength concrete. However, this can only be achieved if the volume of concrete is reduced to an extent that compensates for the higher cement content with lower water/cement ratio in high strength concrete. Currently the limitation lies in the minimum water content to obtain the needed consistence (even with the latest generation of superplasticizing admixtures available). Lower water/cement ratio for higher concrete strength can only be realized with higher cement content. Hence the volume of higher strength concrete has to be reduced to the extent that the total amount of cementitious materials for the concrete structural element is sufficiently reduced. This posts the major challenge to designers for the structural concrete elements which should also include the amount of steel reinforcement required.

One changing approach in "Reuse" is to reuse structural components when an existing concrete structure is to be demolished (often for economic reasons, land cost) rather than its intended design working life. An example of such approach is reported in a study by Ong (2010) on "design for deconstruction" (DfD) jointly by the Housing and Development Board of Singapore and National University of Singapore. The concept was validated with half-scale model bean elements joined as beams, deconstructed and reconstructed before load testing. In such applications, a completely new BIM system is also developed to store the original design information as well as the method of deconstruction and reconstruction with potential for longer beam spans.

Coarse recycled aggregate (RA) from demolition wastes may not be suitable for structural concrete production and to be assessed on a case-by-case basis. However, BS 8500 (2016) has adopted a new term "crushed concrete aggregate, CCA" to replace the previously more general term "recycled concrete aggregate, RCA". It is limited in the source of the concrete as part of the requirements for coarse crushed concrete aggregate. "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 by storage or processing, the only requirements are for aggregate size, fines content, drying shrinkage and resistance to fragmentation" as indicated in Table 2 of BS 8500-2 (2016). Limitations on the use of coarse CCA are given in Table 3 of BS 8500-2. The maximum strength class is C40/50 and for exposure classes of X0, XC1 to XC4, XF1 and DC-1. These are more demanding than for coarse RA.

There is no guidance on the use of fine CCA in concrete. However, Note 1 in BS 8500-1 (2016) 4.3.6 states that "Clean fine CCA is suitable for use in concrete". Concern is for presence of gypsum plaster which may not be absent for sources of concrete indicated in Table 2 of BS 8500-2 (2016) quoted above. Hence, "the use of fine CCA is left to the project specification, which can take account of the particular source of CCA" (4.3.6 BS 8500-2: 2016). Further studies on the characteristics of fine RA and fine CCA may lead to guidance being included in codes.

4.0 FUTURE DEVELOPMENTS

After the brief review of the historical PAST and some of the issues related to concrete at PRESENT, it leads to consideration of developments in the FUTURE.

4.1 Progress To-Date

The reliance of past track records and prescriptive approach in codes and standards for concrete has hindered innovative advances to be adopted in practice. Constituents for concrete and concrete technology have made significant advances over the past few decades (1980's to 2019). For example "Ordinary Portland Cement" in the past changes to the current 34 types of cement in BS EN 197-1 (2011) and in the future the low carbon footprint alkali-activated cementitious materials and concrete (PAS 8200: 2016). At early days, plasticizing and retarding admixture was based on lignosulfonates leached from the natural wood pulps in producing white colour paper. The latest generation of polycarboxylate is now an engineered product for which both plasticizing and set-retardation function can be specified for specific project requirements. Future development may include potential for enhancing corrosion resistance of embedded steel reinforcement. Fibre-reinforced composites are the newly fast developing structural medium. Recycled aggregate for structural applications is specified with a set of well defined requirements for coarse crushed concrete aggregate (CCA) and with the potential also for fine CCA to be incorporated. Together with crushed stone fine aggregate, they will eventually replace the diminishing source of natural sand for concrete.

The traditional approach in specifying concrete and its constituent materials adopts mainly standard prescriptive assessment methods and acceptance criteria. In most cases, more often than otherwise, they rely on semi-empirical approach for conformity with little direct application to the site requirements. Hence, they mainly served the purpose of meeting the specified requirements which may not be those for the actual construction processes. There is a need to develop a more site performance-based system of assessment with target acceptance values related to the applications on site. Two such examples are presented to illustrate this change of emphasis. They serve to illustrate ways towards enhancement to the current standard test methods and may still need further refinements to meet the actual needs on site.

4.2 Passing Ability of SCC

For SCC the passing ability classes (PJ1 and PJ2 to BS EN 12350-12 2010) using the J-ring are based on two configurations of J-rings. They do not necessarily simulate the configuration of reinforcement bars in an actual structural element. Passing ability depends on two factors, the clear gap spacing between reinforcement bars and the extent of blockage by the reinforcement bars over a given sectional area (expressed as a blockage ratio), which is the factor not considered in BS EN 12350-12 2010). A modification of the J-ring of 300 mm diameter to one of 500 mm (P-ring for passing ability) enables a greater number of combinations of the factors, clear gap spacing and blocking ratio. This has been discussed by Tam (2019) based on the use of the P-ring reported by Chan *et al* (2010). An example is the case of a raft foundation with 40 mm bars at 100 mm centres in both directions resulting in a clear gap spacing of 60 mm and a blocking ratio of 40 % on site. With the P-ring, this is approximated with 16 x 40 mm diameter bars giving a clear gap space of 58 mm and blocking ratio of 41 %. On the other hand J-ring with wide gap has clear gap space of 59 mm but blocking ratio of only 23%. With a larger diameter of 500 mm for the P-ring, the concrete has reached a slower flow rate by the time it meets the bars compared to the case of the J-ring of 300 mm diameter.

The passing ability in the J-ring test is based on the difference in height of the concrete before and after it has flowed through the clear gap spacing and the blocking effect of the bars (J-ring step). This is disadvantaged by the fact of the small difference in J-step specified (≤ 10 mm) and the lack of repeatability (4.6 mm) and reproducibility (7.8 mm) for the clear gap spacing of 41 mm (BS EN 12350-12 2010). Tam *et al* (2005) proposed adopting the ratio of the P-ring flow diameter to the slump flow diameter as the Passing Ability Index (PAI). ASTM C1621 (2017) first published in 2007, also based the assessment on these two diameters to indicate the level of blockage but specified the difference between the two flow diameters. It defines the difference of (0 to 25 mm) as "no visible blocking", (> 25 to 50 mm) as "minimum to noticeable blocking" and (> 50 mm) as "Noticeable to extreme blocking". In the case of PAI, it takes into account the actual value of the value of the slump flow diameter For example, when the slump flow diameter is 700 mm (mid-point of 550 to 850 mm), the corresponding ratios in PAI are (1.00 to 0.96), (< 0.96 to 0.93) and (< 0.93).

4.3 Cold Joint Formation

The casting of raft foundations often calls for over 10,000 m^3 of continuous placement of concrete taking up to over 2 days. In some instances, delay may arise from arrival of RMC delivery due to traffic accidence/congestions or stoppage due to break down of pumping system. There is always the uncertainty how long such a delay can be tolerated before issues of potential cold joint formation which may impair the concrete quality in the zone making up of the already placed concrete with the fresh concrete to be placed over it. A definite cold joint is present between hardened concrete and newly placed fresh concrete for which the interface is treated to enhance the bond at the interface. However, it is less clear when the already placed concrete is only partially set. This uncertainty remains unresolved and there is as yet no method to assess the situation on site. A series of preliminary studies was initiated at NUS and some of the findings have been reported by Tam *et al* (2017). When the zone of concrete consisting of the already placed and newly placed concrete is vibrated the resultant effect is a reduction in the flexural strength determined by testing a vertically cast interface of a beam in flexure (modulus of rupture mode). No distinct line indicating a joint cold is observed. The delay time was up to 6 hours in the laboratory test. Although this finding does not resolve the issue at hand, but another finding as part of the study provided an approach to assess the state of the already placed concrete. Based on the current approach to determine the potential cold joint formation time using the ASTM C403 (2016) method, the time for the wet-sieved mortar from the concrete to reach a penetration resistance of 3.5 MPa, the corresponding penetration resistance of the same concrete was found to be approximately 10 MPa for the designed concrete tested. Since a single concrete was investigated, the equivalent penetration resistance of concrete is valid only for the designed concrete tested. However, the concept that the in-situ concrete already placed may be tested for its penetration resistance before newly fresh concrete is introduced may be adopted as an interim approach. By correlating the time for the wet-sieved mortar of project concrete to reach 3.5 MPa and the corresponding penetration resistance of the same concrete at that time, this may be taken as the criterion for expecting potential formation of a cold joint. This may serve as an interim measure until further investigations on the bond strength in the zone consisting of both already placed and newly placed concrete of different compositions. Other parameters may include treatment of the surface of the already placed concrete with bonding agents (including cement slurry) or by increasing the strength class of the yet to be placed new concrete for intermixing by internal vibrators to compensate for the reduction of strength noted in the study. Alternatively, acceptance criterion for an approved delay based on performance testing of flexural strength considered in the study as part of the initial tests of the designed concrete may be developed.

4.4 Carbon Dioxide Challenge

The production of Portland cement is accompanied by a significant generation of carbon dioxide. Although recent advances in cement production technology has reduced the amount of carbon dioxide released from the former level of 1,000 kg per ton of cement to around 800 kg, due to increasing demand in cement for concrete in economic development, this presents a challenge to minimize global warming. Injection of carbon dioxide into readymixed concrete was a new technology founded by R. Niven of CarbonCure Technology in 2007. The CO_2 introduced during production has been shown to benefit some properties of concrete, such as strength and durability (Monkman *et al*, 2016). As a mitigating approach, new technologies are developed in relation to carbon dioxide sequestration in cementitious construction materials. Carbonation of concrete is a well known phenomenon which occurs naturally during the service life of concrete. However, the amount of carbon dioxide removed from the atmosphere in this process is not significant compared to the amount released in cement production for the concrete. The new approach is to induce carbonation in concrete by curing concrete precast elements under high concentration of carbon dioxide and pressure/temperature to accelerate the carbonation process. In this way, sequestration of carbon dioxide from industrial processes such as burning of coal for energy generation can be captured to avoid being released to the atmosphere. A recent publication on this field edited by Pacheco-Torgal *et at* (2018) reported on the development of this technology.

4.5 Assessing Performance of Mortar in Lieu of Concrete

The study on concrete performance may be based on the mortar fraction of the concrete (e.g. stetting time of concrete with wet-sieved mortar). The combined effect of grading, particle shape and surface texture of fine aggregate on consistence may be assessed based on mortar with adjustment of plasticizer dosage needed for a given consistence. The concept is already practiced in admixture usage with a standard mortar. A new approach is proposed by testing mortar using a modified procedure in the flow table test for consistence of concrete. The initial slump or flow diameter is an indication of the yield strength. The subsequent increase in the flow diameter by increasing number of jolts of the flow table is an indication of the plastic viscosity, analogous to concept in the Bingham model for rheology of concrete. The results will be reported at a later date.

5.0 CONCLUDING REMARK

In summary, in order to have sustainable concrete construction in the FUTURE, it calls for:

(a) Urgent establishment of durability monitoring of existing and new infrastructures to enable calibration of explicit durability design equations for carbonation and chloride ingress.

(b) Develop usage of marginal aggregates for concrete such as both coarse and fine RA and RCA

(c) Develop design criteria for design with concrete using low carbon footprint cementitious binders.

(d) Develop truly performance-based assessment methods for both conformity testing in laboratory and their corresponding test methods for site application.

(e) Develop low carbon footprint cement using SCM from other industries

(f) Develop methods for the sequestration of carbon dioxide in concrete. ■

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