Vol. 1 No.2July-December 2013

Journal of Thailand Concrete Association
วารสารวิชาการสมาคมคอนกรีตแห่งประเทศไทย

SUSTAINABLE DEVELOPMENT FOR CONCRETE CONSTRUCTION : DESIGN AND MATERIALS

Somnuk Tangtermsirikul[1]*, Chalermchai Wanichlamlerd[2], Krittiya Kaewmanee[1], Taweechai Samrnwanich[3], Pitisan Krammart[4], Ittiporn Sirisawat[5] and Jittbodee Khunthonkeaw[6]

[1] School of Civil Engineering and Technology, Sirindhorn International Institute of Technology (SIIT), Thammasat University
[2] Construction and Maintenance Technology Research Center, School of Civil Engineering and Technology, Sirindhorn International Institute of Technology (SIIT), Thammasat University
[3] Department of Civil Engineering, Faculty of Engineering, Burapha University
[4]Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology, Thanyaburi
[5] Department of Civil Engineering, Faculty of Engineering, Srinakharinwirot University
[6] Baker Hughes Asia Pacific Corporation

ARTICLE INFO:

Received:November. 3, 2013
Received Revised Form:December 15, 2013
Accepted:December 20, 2013

**Corresponding Author,*
Email address: somnuk@siit.tu.ac.th

ABSTRACT :

A concept of sustainabledevelopmentforconcretestructure construction in Thailand are described in thispaper. Observation on the practices during the pastdecadesshowedinadequate attentions on good practices resulting insomelowquality and short-life structures. Solutions have been proposed for all practicingsteps, i.e. 1) analysis and design, 2) materialsselection and specification, 3) construction, and 4) maintenance, for achievingsustainable practices. This paperdescribesonlysomeexamples in the aspects of design and materials. For design, the new Thailand Building Codes Project launched by the Department of Public Works and Town& Country Planning isa successful effort. The Codes includedurability and service life design whichappears for the first time in Thailand. For materials, problems on specification and examples of application of cementreplacingmaterials are described. A multi-binder concept isintroduced as an example.

KEYWORDS : Sustainable Development, Durability and Service Life Design, Carbonation, Chloride-Induced Steel Corrosion, Sulfate Attack, Cement Replacing Materials

1. Introduction

It is clear that the construction practice in Thailand still involves problems. Reportsshowed that many low quality structures caused by inadequate attentions on good practices have been found [1, 2]. It was also shown that there are still many opportunities to reduce burdens on environment by proper construction practices.Many countries have been spending large amount of money for repair and maintenance of their structures. Those low quality structures were normally caused during one or more of the following 4 steps of practice i.e. 1) analysis and design, 2) materials selection, and specification, 3) construction and 4) maintenance. Since it is not possible to elaborate all issues in details in this paper, only some examples of efforts to establish good practices in Thailand for steps 1) and 2) will be briefly introduced.

2. Statement of Problems

Inspection on deterioration of concrete structures in different areas in Thailand has been performed for years. Various types of damage have been observed. Structural damages caused by loading were found in some special cases. Although most of the severe load-inducing structural damages call for immediate repairs, they can be found in much smaller number of cases when compared with the damages due to durability problems. This fact emphasizes that the current practices are not sufficient to guarantee durability as well as designed service life of the structures and then leads to needs of a large quantity of maintenance works. So, it is obvious that practices which enable us to obtain durable structures should be employed as standards of practice for construction, and the new standards of practice should be applicable to various construction and environmental conditions.

3. Proposed Solutions

The authors' research group has been spending efforts to promote the concept of sustainable practice for concrete construction in Thailand during the last two decades. The following practices are emphasized.

- practicing a design considering durability and service life
- selecting proper materials and mix proportion of concrete
- practicing good construction control and inspection
- practicing good maintenance

It is clear that to have good quality structures with satisfactory service life, all the 4 mentioned steps of practice can not be ignored. There are many opportunities to improve the level of sustainability for construction in Thailand through the improvement of these 4 steps of practice. Due to the limitation of the paper length, only some examples of efforts in Thailand in the first 2 steps, steps of design and material selection and specification will be elaborated here. Without good practices in the first 3 steps, good quality structures cannot be obtained right after the construction. In addition, lack of proper maintenance also results in deterioration with the rate faster than expected. In many earlier developednations, the budgets used for maintaining structures are more than half of their total construction budgets. In Thailand, a rough estimation of the figure by the authors is approximately 30%. Figure 1 shows an example of data from a major public authority in Thailand. It has been realized that the overall maintenance budget did not usually go along with the economic condition while the total construction budget usually did. Higher of this figure means there is less budget for new construction. Such situation is certainly considered not acceptable for developing economies.

3.1 Design Solution : Durability and Service Life Design

Most concrete structures improperly designed without considering conditions of construction and surrounding environment as well as possible durability problems have shorter service life than they should. In this section, a concept for design consideringdurability, adopted by the Department of Public Works and Town and Country Planning as the Thailand design standard, is briefly introduced. Most of the design equations, charts and tables were established based on the works done by the research group of the authors [3, 4, 5] together with those modified from some foreign standards. Only 3 major deterioration types i.e. chloride-induced corrosion, carbonation and sulfate attack are briefly introduced as examples here.The items concerned in durable concrete design are based on selection of type of binders, and concrete mix proportion in addition to the cover thickness. The details of concrete design depend on the concerned durability problems. As examples, brief explanations ofdesign or specification for 3 durability problems i.e. chloride-induced steel corrosion, carbonation and sulfate attack are described below.

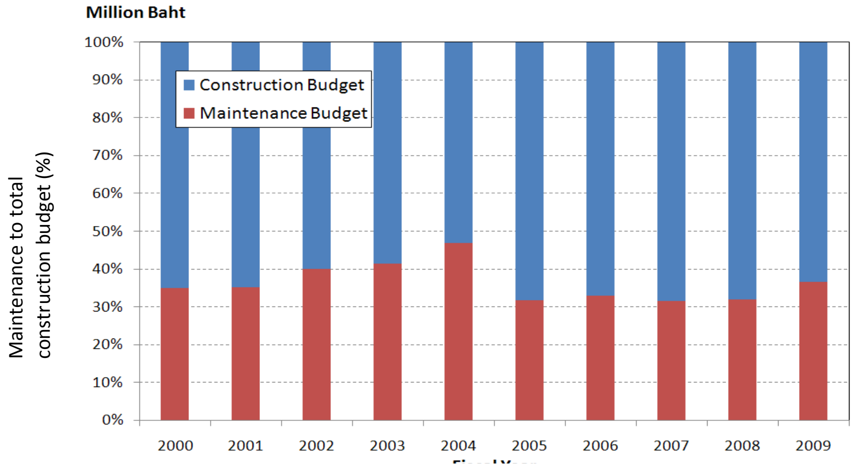

Figure 1 Ratio of maintenance to total construction budgets of a major public authority in Thailand

3.1.1 Chloride induced steel corrosion

In this section, only the case of chloride entering the structures from the outside environment is considered. In the design, the chloride content at the surface of steel bars must be controlled to prevent initiation of steel corrosion as shown in Equation 1.

$$C_d \le C_{\lim} \quad (1)$$

where,

$C_{\lim}$: Critical chloride content that causes steel corrosion (see Table 1)

C_d : Chloride content at the surface of the steel bar nearest to the concrete exposed surface (%wt. of binder), coming from the environment, which can be estimated from

$$C_d = (C_s - C_0)\left[1 - erf\left(\frac{c}{2\sqrt{D_a t_r}}\right)\right] + C_0 \quad (2)$$

where,

c : Concrete cover thickness (cm)

D_a : Apparent chloride diffusion coefficient (cm2/year)

t_r : Repair-free service life of the designed concrete structure (year)

C_s : Surface chloride content of the concrete structure (%wt. of binder) (see Table 2)

C_0 : Initial chloride content at the surface of steel in concrete (%wt. of binder)

erf: an error function

Figure 2 shows an example of the relationship between the apparent chloride diffusion coefficient of a non-cracked cement-only concrete and water to binder ratio.

Table 1 Critical chloride content

Type of Binder	Critical Chloride Content (%wt. of total binder)
Cement (OPC) only	0.45
Cement (OPC) + Limestone powder (LP) - LP to total binder ratio is not more than 0.15	0.45
Cement (OPC) + Fly ash (FA) - FA to total binder ratio is less than0.15 - FA to total binder ratio is not less than 0.15 but less than 0.35 - FA to total binder ratio is not less than 0.35 but not more than 0.50	 0.45 0.35 0.30
For OPC+LP+FA, if LP to total binder ratio is less than 0.15, the values of OPC+FA shall be used.	

Table 2 Chloride content at the surface of concrete

ServiceLife(years)	10	20	30	40	50
DistancefromSeashore(m)	Chloride content, C_s)%wt. of concrete(				
Splash	0.971	1.233	1.391	1.504	1.592
0 m	0.299	0.389	0.453	0.506	0.551
100 m	0.135	0.176	0.205	0.229	0.249
250 m	0.061	0.079	0.092	0.103	0.112
500 m	0.041	0.054	0.063	0.070	0.076
1000 m	0.040	0.052	0.060	0.067	0.073

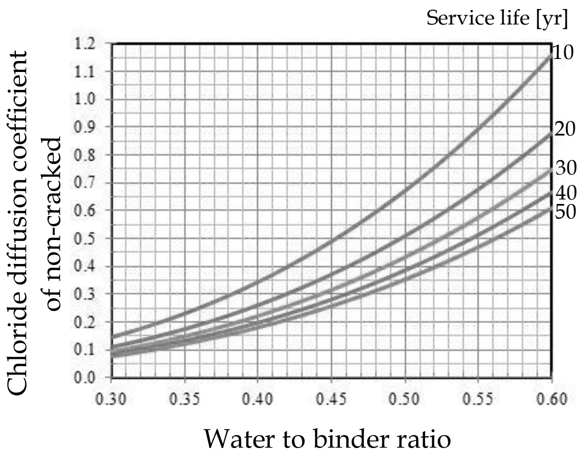

Figure 2 Relationship between apparent chloride diffusioncoefficient of non-crackedcement-onlyconcrete and water to binder ratio

3.1.2 Carbonation

Spalling of concrete cover due to carbonation can be observed in many infrastructures in Bangkok. Quality and thickness of concrete cover of the structures should be sufficiently provided to ensure that the corrosion of reinforcement due to carbonation does not take place during its designed repair-free service life. The thickness of concrete cover should not be smaller than the depth of carbonation during the service life (see Equation 3).

$$X_c \leq c \tag{3}$$

where,

c : Concrete cover thickness (mm)

X_c : Depth of carbonation (mm) which can be estimated from

$$X_c = \alpha_1 \alpha_2 k t^{0.5} \tag{4}$$

where,

α_1 : Effect of rain subjection (see Table 3)

α_2 : Effect of severity of the environment (see Table 4).

t : repair-free service life

Table 3 Coefficient for effect of rain subjection on carbonation

Condition of Rain Subjection	α_1
Can be wetted by rain or water	0.95
No possibility of rain/water subjection	1.00

Table 4 Coefficient for severity of carbonation

Level of Severity of Carbonation Environment	α_2
Typical	0.65
Medium Severity	0.85
High Severity	1.00

The severity of the carbonation environment is specified from the estimated average relative humidity and average CO_2 concentration of theenvironment of the designed structure throughout its service life as in Figure 3 [6]. t_r is the repair-free service life (years). k is the carbonation coefficient which can be derived from

$$k = 1.5k_r(w/b)^3 \quad (5)$$

where,

w/b : Water to binder ratio

k_r : Effect of fly ash on carbonation coefficient (see Figure 4).

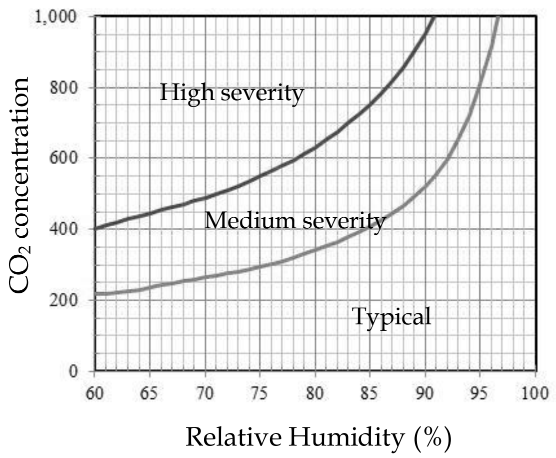

Figure 3 Degree of severity of carbonationenvironment

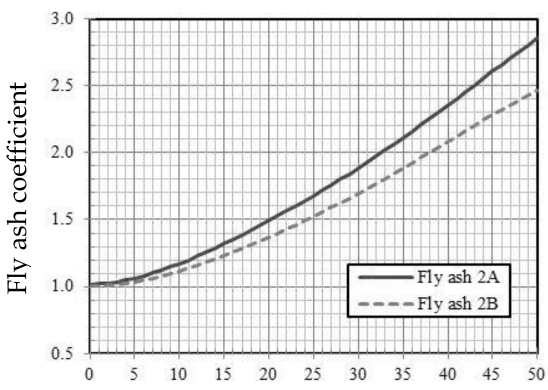

Figure 4 Coefficient k_r for each type of fly ash indicating effect of each fly ash on carbonation reaction

3.1.3 Sulfate Attack

Different types of sulfate cause different deterioration mechanisms and the new building code includes this fact. Sodium sulfate causes expansion whereas magnesium sulfate mainly causes conversion and dissolution of calcium silicate hydrate with less expansion [5]. Different recommendations are given for each type of sulfate environment. It is noted that only a few codes have provided separate sulfate resisting specifications for different types of sulfate. Table 5 shows classification of level of severity of sodium sulfate environment and recommended types of cementitious material and conditions of mix proportion for sodium sulfate resisting concrete. In case that fly ash is used to improve sodium sulfate resistance, the minimum amount of fly ash, giving an equivalent expansion of the fly ash concrete to that of the concrete using Type 5 cement (sulfate-resistingcement), can be estimated from Figure 5. Table 6 shows classification of level of severity of magnesiumsulfate environment and recommended types of cementitious material and maximum water to binder ratioformagnesiumsulfate resisting concrete.

Table 5 Classification of level of severity of sodium sulfate environment and recommendation for mixture

Level of Severity	Concentration of Sulfate (SO_4^{2-})		Recommended Binder Type	Max. w/b
	In Water (ppm)	Soluble Sulfate Content in Soil (% by weight of soil)		
Low	Less than 150	Less than 0.1	-	-
Medium	150-1,500	0.1-0.2	OPC 2 or OPC5 or OPC 1 with pozzolan	0.5
Severe	1,500–10,000	0.2-2.0	OPC5 or OPC 1 with pozzolan	0.45
Very severe	Higher than 10,000	Higher than 2.0	OPC 1 with pozzolan or OPC 5 with pozzolan	0.40

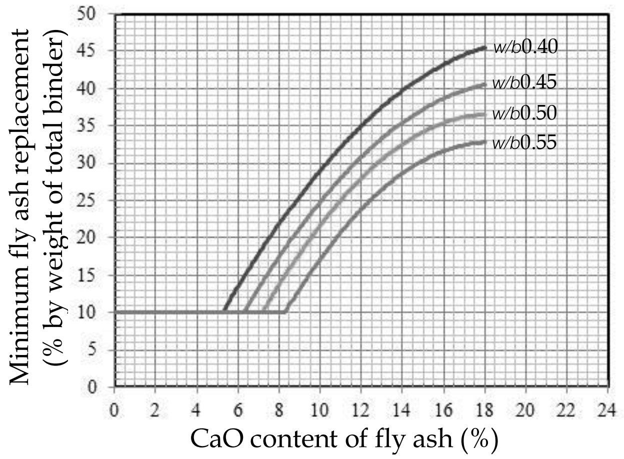

Figure 5 Minimum fly ash replacement percentage to obtain an equivalent sodium sulfate resistance of the OPC Type 5

Table 6 Classification of level of severity of magnesium sulfate environment and recommendation for mixture

Level of Severity	Concentration of Sulfate in Water (ppm)	Recommended Binder Type	Max w/b
Low	Less than 300	-	-
Medium	300 – 1,000	OPC 1 or OPC 2 or OPC 5	0.5
Severe	1,000 – 3,000	OPC5	0.45
Very severe	Higher than 3,000	OPC 5	0.40

3.2 Materials' Solutions

Major problems regarding practices on materials are summarized as follows.

- Insufficient concerns on environment and energy conservation: Initial cost and familiarity with traditional materials seems to be the priorities.
- Material specification does not consider various necessary properties especially those related to long term durability but mainly only strength is concerned.
- Too prescriptive and rigid specification together with insufficient knowledge of practitioners make it difficult to apply new and more sustainable materials.
- Improper adoption of foreign specifications which do not suit local conditions.

An example is that standard for cement in Thailand does not cover blended cement in a most beneficial way. As of the cement replacing materials

(CRM)usage, there are various types of CRMs which application including pozzolanslike fly ash, slag, silica fume, RHA, bio-fuel ashes, as well asnonpozzolanslike limestone powder. Though there are various materials with technically high potential, only fly ash is widely utilized in Thailand. This is due to insufficient studies, standards, and specifications for the others. Here, only fly ash and limestone powder which now have real application and have great impact on the concrete industry in Thailand will be introduced. The goal of the development is to make success of the application of multi-binder system in Thailand.

3.2.1 Fly ash

There are difficulties around the world to achieve effective utilization of fly ash or even to get rid of it. The most effective use of fly ash at present, by considering both volume and value, seems to be in the area of concrete. The use of fly ash as a cement replacing material is believed to be beneficial in both environmental and quality improvement aspects. Although some properties of fly ash concrete are possible forconcrete areinferior than those of the concrete without fly ash, the use of fly ash to partially replace cement improves many other properties of concrete especially durability [5, 7, 8, 9].A proper use of fly ash based on type of construction work and the service environment that a constructed structure is located is considered to be most rational.Though there have been worldwide studies, indicating the benefit of using fly ash in concrete, fly ash has still not been effectively utilized in most countries until now due to many reasons. In Thailand, fly ash has been domestically available since the end of the 1970's. However, the use in concrete was just started in early 1990's and the effective use of fly ash was just materialized since 1997. Since 2004, approximately more than 80% of the fly ash produced in Thailand have been used as a partial cement substituting material for both quality improvement and cost reduction of concrete. Table 7 shows the estimated fly ash annual consumption in concrete construction industry in Thailand.

Table 7 Annual fly Ash consumption in Thai concrete industry

Year	1998	2000	2002	2004	2006	2008	2009	2010
Fly ash consumption (x1,000 tons)	400	950	1,400	1,850	2,000	1,850	1,750	1,850

a) Typical characteristics of fly ash in Thailand

From the data of Thai fly ashes observed continuously for more than 10 years, since 1992, together with the report of a study which cover 40 types of fly ash from 24 generating plants in Japan [10], it can be seen that the chemical composition of fly ashes in Thailand covers a wider range than that of Japan and typically majority of the Thai fly ashes have higher CaO but lower SiO_2 and fineness, especially for the fly ash obtained from Mae Moh power plant. This is mainly because, in addition to the differences of the types of the plants and processes, Thailand uses many sources of coal both local and imported ones. The domestic coal is lignite while most of the imported coals are bituminous coals. For physical properties, majority of the Thai fly ashes, particularly the Mae Moh fly ash,also have lower specific gravity, Blaine fineness and LOI than the Japanese fly ashes. From the data of Blaine fineness and the amount retained on sieve#325, the Thai fly ashes are thought to be coarser. However lower specific gravity of the Thai fly ashes denotes that the Thai fly ashes have more cenospheres and plerosheres. The lower loss on ignition of the Thai fly ashes is considered to be due to higher allowable burning temperature of the coal powder in Thailand than that allowed in Japan due to the limitation of the emission.

b) Properties of concrete with fly ash

As generally known, fly ash has advantages over cement-only system in many performances, i.e. improved workability and pumpability, lower heat of hydration, lower autogenous and drying shrinkage (the latter if cured well), higher longterm strength, lower permeability, improved chloride penetration and sodium sulfate resistance, lower alkali aggregate reaction potential, while on the contrary, worsens some properties like delayed setting and early strength, lower carbonation and magnesium sulfate resistance.

c) Application of fly ash in concrete

Ready-Mixed Concrete : Fly ash is normally used to replace cement in the ranges of 10 to 30% by weight of the total binder. Fly ash concrete has become a conventional concrete for ready-mixed concrete industry. Many ready-mixed concrete companies started to launch special concrete with fly ash such as marine concrete, sulfate-resisting concrete, self-compacting concrete, low-heat concrete, etc. since late 1990's. Some high volume fly ash concrete were also practiced in Thailand with the maximum fly ash content up to 55% of the total binders for self-compacting concrete, 50% for low-heat concrete and 68% for roller-compacted concrete for dam construction. The ready-mixed concrete industry is currently the major consumer of fly ash in Thailand.

Precast Concrete and Concrete Products : For precast concrete and concrete products, fly ash is normally used in the works that does not require early strength such as non-prestressed concrete. For the prestressed concrete industry, fly ash is also used but with a maximum cement replacement of only up to 10%. The exception may be in the case of self-compacting concrete application in which fly ash may be used up to a range of 30% to 50% even in prestressed concrete work.

3.2.2 Limestone powder (CaCO3 powder)

Fly ash has been successfully utilized in concrete industry for almost two decades in Thailand. It has been proved to enhance many properties of concrete and has become the most popular cement replacing material for concrete industry in Thailand. However, fly ash is also known to reduce some performances of concrete such as slow setting, low early strength, low magnesium sulfate resistance, and high sensitivity to curing, etc. These limit the use of fly ash in some applications. There are several more types of cement replacing materials available in Thailand. Some are in the stage of R&D but some have already been utilized and have high potential.

Limestone powder, LP, is one of the CRMs, though may be considered as a part of fine aggregate in some countries, which has high potential to be used in concrete in Thailand. It should be noted that the application of LP as a part of fine aggregate is not popular in Thailand. This is due mainly to its higher price relative to the available fine aggregate. Limestone powder usually contains calcium carbonate as the major component. The content of calcium carbonate is usually higher than 80% by

Other CementitiousProducts : Some cementitious material products which use fly ash to replace cement in the production are such as cementitious fibered roof tile, cementitious fibered panel, etc. In this category, fly ash is normally used up to a maximum of 30% of the total binder.

Blended Cement : Some cement companies have spent their efforts to introduce ready-blended fly ash cements into the concrete market in Thailand. Most of the introduced cements are in the form of cements for durability purposes such as marine cement, having high resistance against sulfate attack and chloride-induced steel corrosion, sulfate-resisting cement, and low-heat cement, etc. However, these cements are not popular. It is more popular to mix fly ash at the ready-mixed concrete plants. The reasons are because 1) ready-blended fly ash cement is more expensive than cement with fly ash as a separate binder, 2) the ratio of fly ash is usually adjusted according to the required performances of concrete when it is used as a separate binder.

Repair Materials : Fly ash is also used in enhancing performances and reducing cost of some repair materials especially grouting materials. Fly ash was also studied for being used as a stabilizer for controlling expansion of expansive cements [11].

weight of the powder. For effective use as cement replacing material, it is usually ground to a fineness higher than that of the cement. When added in concrete, it only slightly involves in reactions but the effectiveness is derived mainly from the physical acceleration of the reaction and filling effect [12].

There are various properties which can be enhanced by the use of LP [12, 13]. LP is known to accelerate the setting times of cementitious systems. The use of LP to replace a portion of cement or fly ash reduces both the initial and final setting times of pastes both with and without fly ash. Partially replacing cement with an appropriate amount of LP improves early strength of concrete. The appropriate amount usually ranges from 10 to not more than 20% depending on the fineness of the LP. The finer the LP is, the higher the maximum replaceable amount will be. Studies on various concrete containing LP showed that many durability properties of the concrete were improved by the LP. The improved properties are such as autogenous shrinkage, drying shrinkage, and sulfate resistance. Some other merits of LP is to reduce curing sensitivity and increase cracking resistance [14].

3.2.3 Ternary binder system

From the author's studies on use of many cement replacing materials, a plan has been made to introduce the multi-binder system to the concrete industry, either in the manners of blended cements or CRMs. This concept is to optimize the use of various CRMs to obtain optimum performances and cost. For example, fly ash and LP can be used in combination to produce concrete which is better than cement-only concrete in almost all performances. This cannot be achieved by the use of only a single type of CRM. For example, shown in Figure 6 are the results of weight loss of mortar specimens in magnesium sulfate solution. The figure shows that mixtures using fly ash as the only CRMdemonstratehigh weight loss (C80FA20 and C60FA40) while the ternary binder mixtures (C80FA15LP5 and C60FA30LP10) result inlow weight loss when compared to cement type 1 mortar (C1). Figures 7 and 8 show the test results of rapid chloride penetration test on mortars with w/b=0.4. It can be seen that when increasing the LP, the chloride penetration of mortars increases if only LP is used to replace cement (see Figure 7). However, when fly ash and LP are used in combination, it is possible to produce mortar with the lowest chloride penetration thanall other single and binary mixtures (see C70FA25LP#04-5 in Figure 8).Performance evaluation of single, binary and ternary binder systems with cement, fly ash and LP are simply summarized for a quick comparison in Table 8.

4. Conclusion

A concept of sustainable development for concrete construction is described in this paper. It was concluded that in order to obtain high quality structures with satisfactory service life, all four steps of practice should be well practiced. The four steps are 1) analysis and design, 2) material selection and specification, 3) construction and 4) maintenance. As an example, the durability design concept discussed in this paper is one of the important components to develop a more sustainable infrastructure development. The design equations are derived based on some mathematical models established by the research group of the author. Only design for chloride-induced corrosion, carbonation-induced corrosion and sulfate resistance specification areintroduced.

For the aspect of development trend in term of materials, two cement replacing materials i.e. fly ash and limestone powder are introduced. Optimizing the use of cement replacing materials by the concept of ternary binder system of cement, fly ash and limestone powder is proposed.

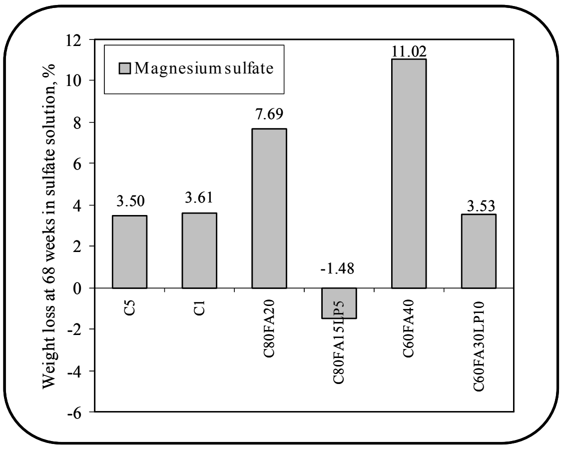

Figure 6 Weight Loss of mortars in magnesium sulfate

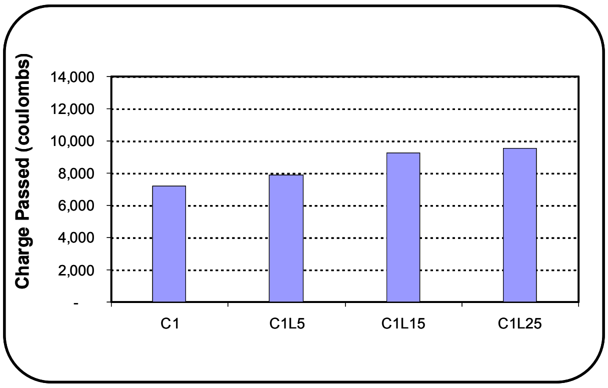

Figure 7 Rapid chloride Penetration test results of mortars

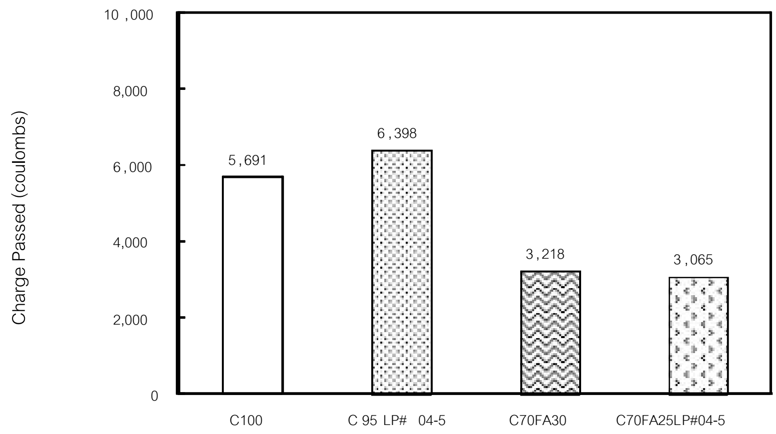

Figure 8 Rapid chloride penetration test results of mortars with ternary binders (w/b=0.4, 28 days)

Table 8 Summary of performances of various binder systems

Binder systems / Properties	Single		Binary		Ternary
	Type I	Type V	C+LP	C+FA	C+FA+LP
Compressive strength					
- Early age	●●●	-	●●●●	●	●●●
- Long-term	●●●	-	●	●●●●	●●●
Slump	●●	-	●	●●●●	●●●
Autogenous shrinkage	●	-	●●	●●●●	●●●
Drying shrinkage	●	-	●●	●●●●	●●●●
Carbonation	●●●●	-	●●●	●	●●
Chloride resistance	●●	-	●	●●●●	●●●
Sulfate resistance					
- Sodium sulfate	●	●●●	●●	●●●●	●●●●
- Magnesium sulfate	●●●	●●●●	●●●	●	●●●●

Remarks: ●●●●= best performance, … , ● = worst performance
FA content ≥ 30%, LP content ≤ 10%, LP size (d_{50}) ranges from 2 – 11 μ m

Acknowledgements

The author would like to acknowledge all his research colleagues as well as his former and present students for their contributions. Appreciations are also given to sponsoring organizations including Department of Public Works and Town and Country Planning, Electricity Generating Authority of Thailand, BLCP Power ltd., and SurintOmya Chemicals (Thailand) co.,ltd., for funding the research works in this paper.

References

[1] Tangtermsirikul, S., Kaewkhluab, T., and Kaewmanee, K., 2003. Information acquisition and structural health monitoring of bridges in Bangkok.___*Proceedings of the Second International Symposium on New Technologies for Urban Safety of Mega Cities in Asia*. 30-31 October 2003, Tokyo, Japan :1333-140.

[2] Tangtermsirikul, S., 2004. Durability design for concrete structures for urban safety in Thailand.*Proceedings of the 3rd International*

Symposium of New Technologies for Urban Safety of Mega Cities in Asia. 18-19 October 2004, Agra, India : 177-184.

[3] Khunthongkeaw, J. and Tangtermsirikul, S., 2005. Model for simulating carbonation of fly ash concrete, *ASCE Journal of Materials for Civil Engineering*. 17(5) : 570-578.

[4] Samranwanich, T. and Tangtermsirikul, S., 2004. A model for predicting time dependent chloride binding capacity of cement-fly ash binder system, *Materials and Structures.RILEM,* 37(270): 387-396.

[5] Krammart, P. and Tangtermsirikul, S., 2004. Expansion, strength reduction and weight loss of fly ash concrete in sulphate solution. *ASEAN Journal on Science and Technology for Development*, 21(4) : 373-390.

[6] Tangtermsirikul, S., Sumranwanich, T., Krammart, P., Khuthongkaew, J. and Sahamitmongkol, R., 2006. Durability design concept for sustainable concrete structures in Thailand, *Proceedings of the 5th International Symposium on New Technologies for Urban Safety of Mega Cities in Asia (USMCA 2006). Phuket*, Thailand, 16-17 November 2006 : 291-300.

[7] Tangtermsirikul, S., Sudsangium, T. and Nimityongsakul, P., 1995. Class C fly ash as a shrinkage reducer for cement paste, *Proceedings of the 5th CANMET/ACI International Conference on Fly Ash, Silica Fume, Slag and Natural Pozzolans in Concrete*, 4-9 June 1995, Milwaukee, Wiscosin, USA, Vol.1 : 385-401.

[8] Tangtermsirikul, S. and Chatveera, B., 1997. Expansion of cement paste and mortar using lignite fly ash, *Supplementary Papers of the 3rd CANMET/ACI International Symposium on Advances in Concrete Technology*. 24-27 August 1997, Auckland, New Zealand : 321-329.

[9] Samranwanich, T. and Tangtermsirikul, S., 2004. A model for predicting time dependent chloride binding capacity of cement-fly ash binder system, *Materials and Structures*, RILEM. 37(270): 387-396.

[10] Yamamoto, T. and Kanazu, T., 1998. Accelerated chemical assessing method for pozzolanic activity of fly ash, *Abiko Research Laboratory Report No. U98047*, Central Research Institute of Power Industry, Japan.

[11] Jakpisal, V. and Limsuwan, E., 2003. Development of shrinkage-compensating cement, *Proceedings of the 1st National Concrete Convention.Kanchanaburi*, 14-16 May 2003, 23-27.

[12] Kakali, G., Tsivilis, S., Aggeli, E. and Bati, M., 2000. Hydration products of C_3A, C_3S and Portland cement in the presence of $CaCO_3$, *Cement and Concrete Research*, 30: 1073-1077.

[13] Kaewmanee, K., Tangtermsirikul, S., and Kasemchaisiri, R., 2006. Effect of particle size of limestone powder on properties of normal concrete and special concrete, *Proceedings of the 11th National Convention on Civil Engineering*, Engineering Institute of Thailand, Phuket, 20-22 April 2006, CD Rom, Abstract : 195.

[14] Hussain, K. ,Choktaweekarn, P., Saengsoy, W., Srichun, T. and Tangtermsirikul, S., 2013. Effect of cement types, mineral admixtures and bottom ash on curing sensitivity of concrete, *International Journal of Minerals, Metallurgy and Materials,* 20(1): 94-105

