CHAPTER 1

INTRODUCTION

1.1 Background

High strength concrete refers to concrete with compressive strength, which is the most single influential parameter to characterize concrete quality, higher than that of concrete conventionally used. This term is quite relative, depending on available materials in each place at a period of time. To be a standard, ACI Committee 363 (1992) defined high strength concrete with compressive strength of at least 6000 psi (41 MPa) at 28 days. While high strength concrete is regarded as concrete with average 28-day compressive strength exceeding 8700 psi (60 MPa) in the recent state-of-the-art report of CEB-FIP (1990).

Not only high compressive strength, but also other mechanical properties of high strength concrete, such as elastic modulus and tensile strength, are promising. Because of high load-resistance capability, high strength concrete can reduce the size of structural members, is compatible to modern architectural designs, and provides benefits in the construction process. Furthermore, high strength concrete tends to be durable in long term; permeability, shrinkage and creep of HSC is reduced. Then, high strength concrete has been used widely for many outstanding structures, for example, Two Union Square in USA (Howard and Leatham, 1989), Gullfaks offshore platform in Norway (Ronneburg and Sanvik, 1990), Ile de Re bridge in France (Cadorat and Richard, 1992), and Baiyoke II Tower in Thailand (Burnett, 1994).

Until now, there have been many attempts from many researchers around the world to raise the attained concrete strength. Advances in concrete technology can roughly categorize high strength concrete into four classes regarding to its strength level, i.e.,

1. High Strength Concrete (HSC) – Compressive strength of HSC is 50-100 MPa. HSC is usually applied in construction industry without much difficulty. It can be made from the commonly available concrete-making materials. There are many methods to

design on mix proportion of HSC, for example that proposed by ACI Committee 363 (1992), CEB-FIP (1990), and Sedran and de Larrard (1996).

2. Very-High Strength Concrete (VHSC) – Its compressive strength varies from 100 to 150 MPa. VHSC can be produced in the laboratory, but reliability of its performance can not be guaranteed in practice. Careful selection of special concrete ingredients is necessary.
3. Ultra-High Strength Concrete (UHSC) – Compressive strength lies in between 150 and 200 MPa. The conventional materials and processing can not produce this type of concrete with proper consistency. An approach for concrete mix design with repeatability is still challenging.
4. Extremely-High Strength Concrete (EHSC) – Compressive strength is greater than 200 MPa. This strength level is formidable with the general concrete treatments. A special manipulation, such as, pressure placing, and thermal or steam curing, is mandatory.

1.2 Production of High Strength Concrete

At the outset of development, mix design of high strength concrete was based primarily on the law of water to cement ratio. Because aggregate is usually hard compared to cement paste, there was no explicit consideration of load-carrying capacity of aggregate in the mix design of high strength concrete. Raising strength of cement paste caused by lowering water/cement ratio with adequate workability promises on increase in concrete strength. Nevertheless, interfacial bond between aggregate and cement paste significantly limits concrete strength.

With advances in concrete technology, compressive strength of cement paste can be achieved in the same degree as that generally acquired by aggregate. High strength concrete should be modeled as a three-phase material comprising bulk cement paste, aggregate, and interfacial zone. Both quality and quantity of all three phases must be concerned in mix design process. In essence, proportioning of the mixtures of high strength concrete consists of three interrelated steps:

1. Selection of suitable constituents as cement, supplementary cementing materials, aggregate, water and admixtures.

2. Determination of relative amount of these materials for economical mixes with desired rheology, high strength, and durability.

3. Careful quality control of every phase of concrete-making process.

Fig. 1.1 shows the schematic diagram for improving concrete strength. The primary key is to reduce internal defects in concrete microstructure, i.e., capillary pores in cement paste, poor interfacial bond, and weak minerals and fissures in aggregate particles. Following in this section reviews the general ideas to achieve high strength concrete of researches recently.

1.2.1 Cement Paste

The most important parameter to characterize the nature and properties of cement paste is porosity. Granju and Maso (1984a, 1984b), and Kolias (1994) explored the relation between porosity and compressive strength of cement paste as exponential functions with coefficients depending on the compressive strength at zero porosity and nature of internal structure of the cement paste. Mehta and Aitcin (1990) concluded that compressive strength could be improved by reducing porosity, grain size of hydrated product, and inhomogeneities in microstructure.

Since it is not easy to measure porosity and normally the porosity of well-compacted cement paste is determined by water/cement ratio and degree of hydration, water/cement ratio has been used to specify the quality of cement paste. The influence of water/cement ratio on compressive strength of hardened cement paste, gathered by Fiorato (1989), is depicted in Fig. 1.2. It is obvious that reduction of water/cement ratio gains more strength of cement paste. However, cement paste mixture with low water/cement ratio tends to be sticky and difficult to handle and place properly into formwork. Thus, use of high-range water reducers (HRWRA) or superplasticizers is required. Compatibility between cementing agents and superplasticizers nevertheless affects efficiency providing workability and strength (Aitcin et al, 1994).

Insufficient compaction significantly reduces the strength of cement paste and concrete due to the presence of air voids. Up to 5 percent loss in strength may be sustained from each one percent of void space in concrete (Davies, 1951). The amount of air void in concrete depends on the efficiency of compaction methods (Neville, 1995). Yudenfreund, Odler and Brunauer (1972), and Yudenfreund, Skalny, Mikhail and Brunauer (1972) applied pressure during placing and yielded cement paste with compressive strength greater than 200 MPa.

Calicium silicate hydrate (CSH) as a main hydration product is believed to influence cement paste strength. Thus, cement with higher amount of dicalcium silicate and tricalcium silicate tends to provide more compressive strength. However, it depends mostly on the morphology of these compounds due to the manufacturing process (Aitcin, 1998).

Pozzolanic materials, such as silica fume, fly ash, blast furnace slag, and rice husk ash, are often used as mineral admixtures in the production of high strength concrete, because these materials can react with calcium hydroxide in cement paste and form secondary CSH. In Chulalongkorn University, the replacement of silica fume at 15% by weight of cement can raise concrete strength up to 20% (Suwankawin, 1996). While, 15% substitution of fly ash results in about 10% increase in compressive strength (Chakpaisan, 1996).

Especially in high strength concrete when some cement grains are not fully hydrated, more moisture content is required after placing. Curing conditions have remarkable influence on concrete strength. Compared to water curing at room temperature, thermal or stream curing leads to a favorable effect on compressive strength (Duyou et al, 1995).

In polymer impregnated concrete, air voids or capillary pores are eliminated by filling with polymers. This may raise concrete hardness up to three times of the unimpregnated one, depending on degree of polymerization (Mikhail et al, 1981). Nevertheless, polymer impregnated concrete seems to be of little interest in the application because of its complicated process and limited implementation.

1.2.2 Interface Zone

The cement paste region lying immediate vicinity of aggregate particles is usually characterized by high capillary porosity and large crystalline hydration product. Furthermore, due to different movement between aggregate and bulk cement paste, microcracks often take place in this area. These are responsible for the poor strength of the interface zone, which may be regarded as the weakest link component in concrete. Nevertheless, the performance of the interface depends on numerous parameters, including, aggregate size and grading, cement content, water/cement ratio, degree of consolidation, and curing condition.

Regarding aggregate geometry, there is a tendency for internal bleeding in concrete containing a large aggregate with a high proportion of poor shape particles (Mehta, 1986). Moreover, the use of small aggregate offers the benefits of an increase in total surface area and therefore reduction of bond stress (Neville, 1997). The packing of ultra-fine particles, such as limestone or siliceous powder, may physically improve initial porosity around aggregate particles (de Larrard, 1989). Fine pozzolanic materials, especially for silica fume, are accredited as potential reactive fillers (Goldman and Bentur, 1989).

1.2.3 Aggregate Strength

Because aggregate is relatively strong compared to other materials, the consideration of aggregate quality is sometimes neglected when high strength concrete is concerned. Aggregate should be hard and strong, as well as contain no weak minerals or defects. Morino and Iwatsuki (1995) reported concrete strength as a function of aggregate crushing strength. The quantitative influence of aggregate of concrete strength was developed empirically by de Larrard and Belloc (1997). The presence of cleavages, intergranular joints and grain-boundary fissures within aggregate particles may be detrimental to concrete strength. De Larrard (1994) suggested that the suitable coarse aggregate used for making high strength concrete should have water absorption less than 1%.

1.2.4 Mix Proportion

The compatibility of amount and characteristic of the concrete constituents significantly influences concrete performance. Water/cement ratio, sand/cement ratio, and sand/aggregate ratio are parameters frequently used in concrete mix design. Water/cement ratio governs the occurrence of hydration reaction, and thus primarily provides the intrinsic strength of binder. Excess water from the hydration process will induce capillary pores in microstructure, but inadequate water content results in poor workability and deficient hydration products. Sand/aggregate ratio indicates aggregate packing or void content among aggregate particles. Not only does high packing of aggregate make concrete mix economic and provide less shrinkage and creep, but also probably gain more strength and durability in the mixture. Sand/cement ratio represents the amount of cement paste relative to aggregate. Insufficient cement paste can not coat all aggregate particles, while surplus of cement paste separates the particles away, thus making them able to not transfer the internal forces properly. To obtain the extreme performance of any concrete, all three parameters need to be optimized.

Tanpao (1995) and Leevanichakit (1995) presented that 3/8-inch and 3/4-inch coarse aggregate in the proportion of 40:60 provides the lowest void content and yields the highest compressive strength with appropriate workability. It was also reported that the ratio of sand to aggregate of 0.45 supplies the most stable mix. Whereas, Mindess (1994) recommended coarse aggregate to fine aggregate ratio of 2.0 as favorable for high strength concrete. The fineness modulus of fine aggregate, according to ASTM C33 in the range of 2.8 to 3.2, is suggested (Cook, 1989, and Howard and Leatham, 1989).

1.3 Objectives and Significance

Nowadays the technology of high strength concrete has been extensively presented and very-high strength concrete with 28-day compressive strength greater than 100 MPa can be manufactured without much effort. Nevertheless, with ordinary concrete-making materials and conventional treatment, concrete strength of 150 MPa seems to be the limit in compression, and the production of ultra-high strength concrete with proper consistency is still challenging.

Therefore, the primary objective of this research is to develop ultra-high strength concrete with 28-day compressive strength exceeding 150 MPa, utilizing common availability of conventional practice. To obtain that, the contribution of concrete components, i.e., cement paste, fine aggregate, and coarse aggregate, on concrete strength will be investigated both via experiments and using simulation models.

Although, special price and more attention have to be paid, with the advance in structural systems and designs, ultra-high strength concrete is appreciated as a potential construction material. Coupled with high-tension steel, it could be a part of a structure that is subjected to heavy compressive loading, such as, a column, shear wall, or pile cap, providing less member dimension and more available space to work or rent.

1.4 Research Methodology

This dissertation can be separated into five major parts, as shown in Fig. 1.3. The first part concerns the development of a concrete micro-mechanical model. With the aid of non-linear fracture mechanics and finite element analysis, behavior of concrete under loading, especially in compression, will be simulated. Afterward, the relationship between physical and mechanical properties of concrete components, i.e., cement paste, aggregate, and interface, and concrete strength in macro-scale will be determined, so that the possibility to obtain ultra-high strength concrete can be evaluated in addition that the specifications of the required materials can be figured out.

Chemical reactions of cement paste, with and without pozzolanic materials, will be intimately analyzed in the second part. Moreover, the experiments on physical and mechanical properties of cement paste will be carried out, in order that the optimized water/cement ratio, which is the most important factor governing performance of cement paste, for the most effective hydration, the lowest void content, and the greatest strength, will be obtained.

Next, the fine aggregate embedded in mortars is examined in the third part. The effects of inclusion of fine aggregate on water content of mixtures will be considered. With the basis of minimum void ratio, the gradation of fine aggregate and sand/cement ratio will be regarded as main parameters both in simulations and in experiments. The workability of mortars will be also considered.

In the fourth part, analysis of various coarse aggregates is included. The physical and mechanical properties of crushed rocks with different sizes will be evaluated. With the hypothesis that strong concrete comes from strong coarse aggregate with low-void gradation, the new idea of strength-based gradation will be developed. Its contribution to concrete strength will be verified and used in a mix design for high strength concrete.

Finally, with the underlying principles already investigated, the mix proportion of ultra-high strength concrete will be developed in the last part. Besides compressive strength, other mechanical properties, such as tensile strength, elastic modulus and Poisson's ratio will be evaluated.

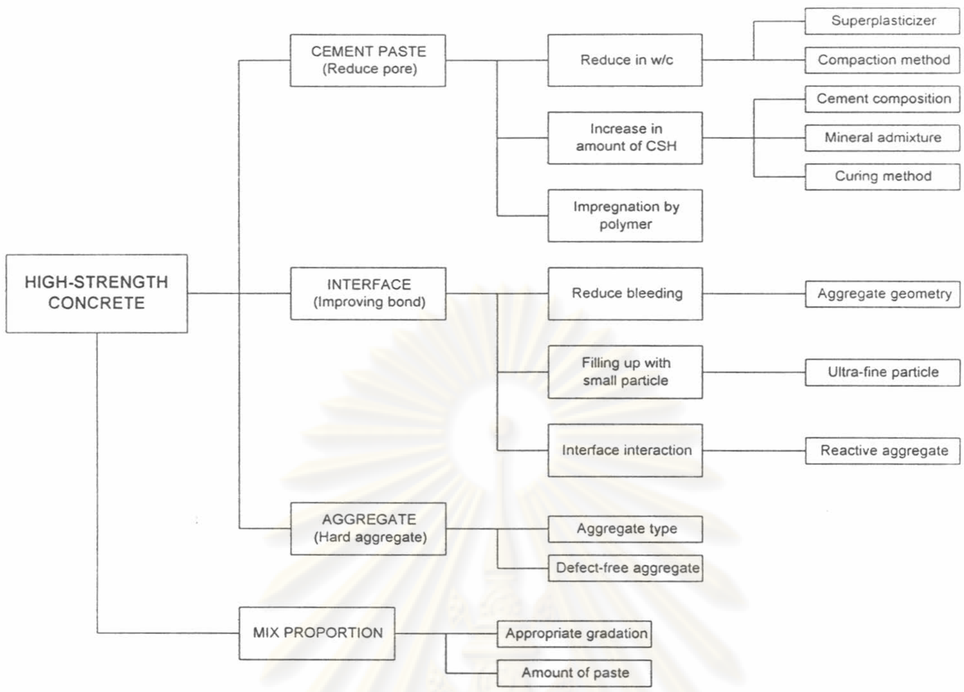

Fig. 1.1 Principal internal factors affecting concrete strength

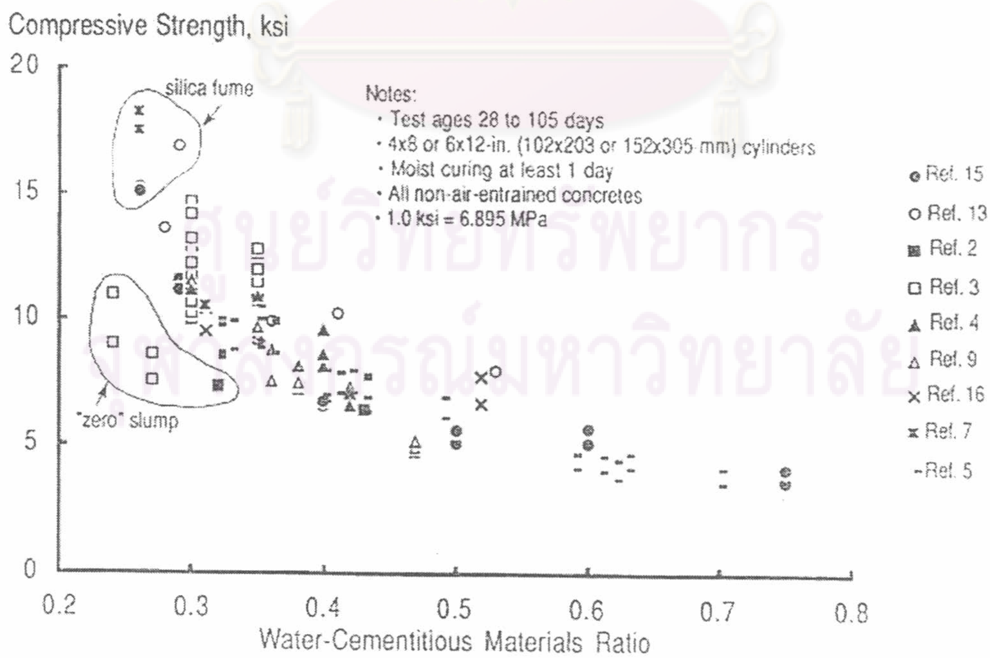

Fig. 1.2 Summary of strength data as a function of water/cement ratio (Fiorato, 1989)

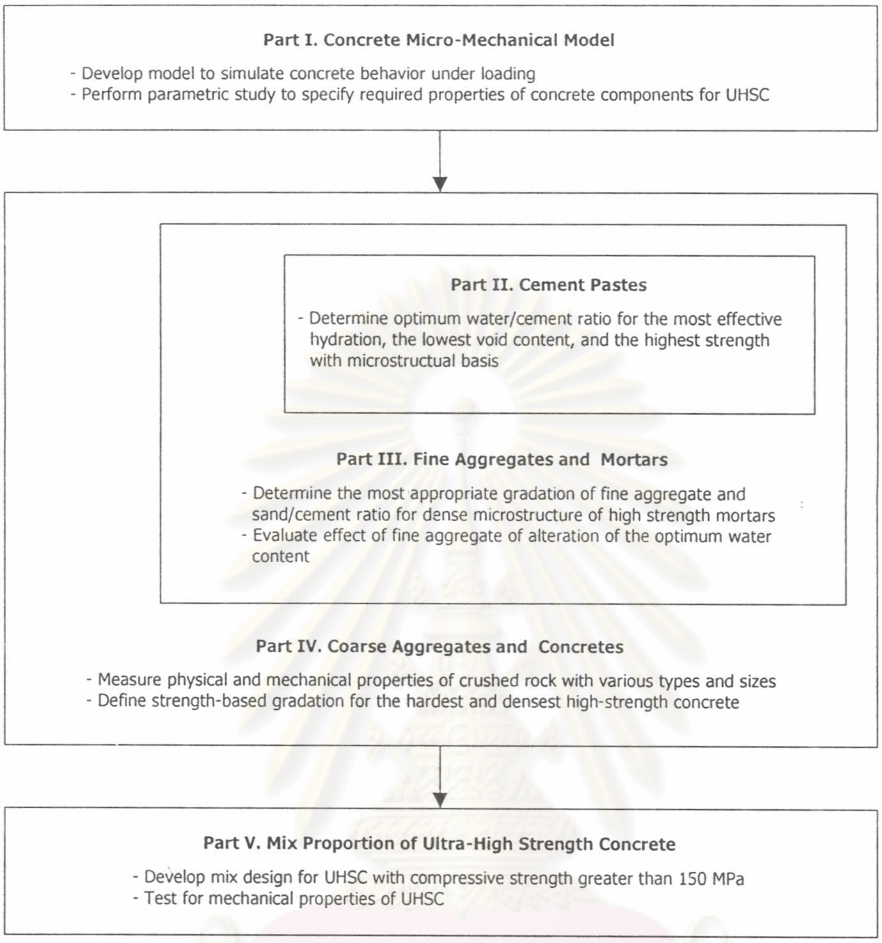

Fig. 1.3 Summarized research program