High-Strength and High-Performance Concrete

- It is important to note the high-strength and high-performance concrete are not synonymous.
- Concrete is defined as “high-strength concrete” solely on the basis of its compressive strength measured at a given age.
- In the 1970’s, any concrete mixtures that showed 40 MPa or more compressive strength at 28-days were designed as high-strength concrete.
- Later, 60-100 MPa concrete mixtures were commercially developed and used in the construction of high-rise buildings and long-span bridges in many parts of the world.

Definitions

- The definition of high-performance concrete is more controversial.
- Mehta and Aitcin[1] used the term, **high-performance concrete (HPC)** for concrete mixtures possessing high workability, high durability and high ultimate strength. [1]

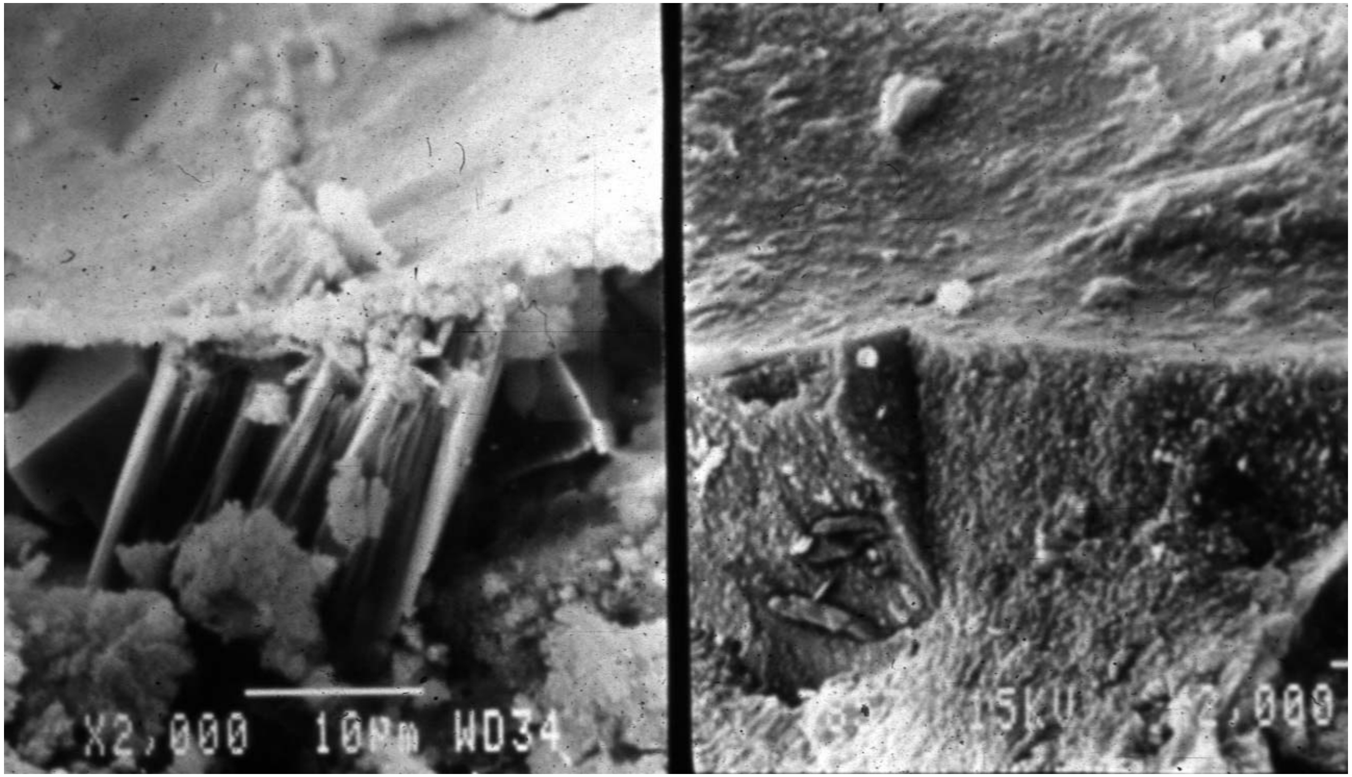
Definitions

- ACI defined high-performance concrete as *a concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practice.* [1]

Typical Classification

Normal Strength	20-50 MPa
High Strength	50-100 MPa
Ultra High Strength	100-150 MPa
Especial	> 150 MPa

Microstructure



Microstructure

- From the general principles behind the design of high-strength concrete mixtures, it is apparent that high strengths are made possible by reducing porosity, inhomogeneity, and microcracks in the hydrated cement paste and the transition zone.

Microstructure

- The utilization of fine pozzolanic materials in high-strength concrete leads to a reduction of the size of the crystalline compounds, particularly, calcium hydroxide.
- Consequently, there is a reduction of the thickness of the interfacial transition zone in high-strength concrete.
- The densification of the interfacial transition zone allows for efficient load transfer between the cement mortar and the coarse aggregate, contributing to the strength of the concrete.
- For very high-strength concrete where the matrix is extremely dense, a weak aggregate may become the weak link in concrete strength.

Materials - Cement

- Almost any ASTM portland cement type can be used to obtain concrete with adequate rheology and with compressive strength up to 60 MPa.
- In order to obtain higher strength mixtures while maintaining good workability, it is necessary to study carefully the cement composition and finenesses and its compatibility with the chemical admixtures.
- Experience has shown that low-C3A cements generally produce concrete with improved rheology.

Materials -- Aggregate

- In high-strength concrete, the aggregate plays an important role on the strength of concrete.
- The low-water to cement ratio used in high-strength concrete causes densification in both the matrix and interfacial transition zone, and the aggregate may become the weak link in the development of the mechanical strength.
- Extreme care is necessary, therefore, in the selection of aggregate to be used in very high-strength concrete.

Materials -- Aggregate

- The particle size distribution of fine aggregate that meets the ASTM specifications is adequate for high-strength concrete mixtures.
- If possible, Aitcin recommends using fine aggregates with higher fineness modulus (around 3.0). His reasoning is as follows:
  - a) high-strength concrete mixtures already have large amounts of small particles of cement and pozzolan, therefore fine particles of aggregate will not improve the workability of the mix;
  - b) the use of coarser fine aggregates requires less water to obtain the same workability; and
  - c) during the mixing process, the coarser fine aggregates will generate higher shearing stresses that can help prevent floculation of the cement paste.

Guidelines for the selection of materials

- The higher the targeted compressive strength, the smaller the maximum size of coarse aggregate.
- Up to 70 MPa compressive strength can be produced with a good coarse aggregate of a maximum size ranging from 20 to 28 mm.
- To produce 100 MPa compressive strength aggregate with a maximum size of 10 to 20 mm should be used.
- To date, concretes with compressive strengths of over 125 MPa have been produced, with 10 to 14 mm maximum size coarse aggregate.

Guidelines for the selection of materials

- Using supplementary cementitious materials, such as blast-furnace slag, fly ash and natural pozzolans, not only reduces the production cost of concrete, but also addresses the slump loss problem.
- The optimum substitution level is often determined by the loss in 12- or 24-hour strength that is considered acceptable, given climatic conditions or the minimum strength required.
- While silica fume is usually not really necessary for compressive strengths under 70 MPa, most concrete mixtures contain it when higher strengths are specified.

Differences Between NSC and HSC

- In normal strength concrete, the microcracks form when the compressive stress reaches ~ 40% of the strength. The cracks interconnect when the stress reaches 80-90% of the strength
- For HSC, Iravani and MacGregor reported linearity of the stress-strain diagram at 65 to 70, 75 to 80 and above 85% of the peak load for concrete with compressive strengths of 65, 95, and 105 MPa.

Differences Between NSC and HSC (2)

- The fracture surface in NSC is rough. The fracture develops along the transition zone between the matrix and aggregates. Fewer aggregate particles are broken.
- The fracture surface in HSC is smooth. The cracks move without discontinuities between the matrix and aggregates.

Mechanical Behavior

- Stress-strain curve is more linear
- The strain corresponding to the maximum stress increases with strength
- The post-peak domain gets steeper
- The ultimate deformation decreases with the increasing strength

Strength

- Based on 289 observations of moist-cured high-strength concrete samples made with Type III cement, Mokhtarzadeh and French obtained the following relationship

$$f_{cm} = f_{c28}\left(\frac{t}{0.89 + 0.97t}\right)$$

Long-term strength

- Iravani and MacGregor suggested the following strength values for sustained loading:
- 70 to 75% (of the short-time loading strength) for 65 MPa concrete
- 75 to 80% for 95 MPa concrete, without silica fume
- 85 to 90% for 105 MPa concrete, with silica fume
- 85 to 90% for 120 MPa concrete, with silica fume

Elastic Modulus

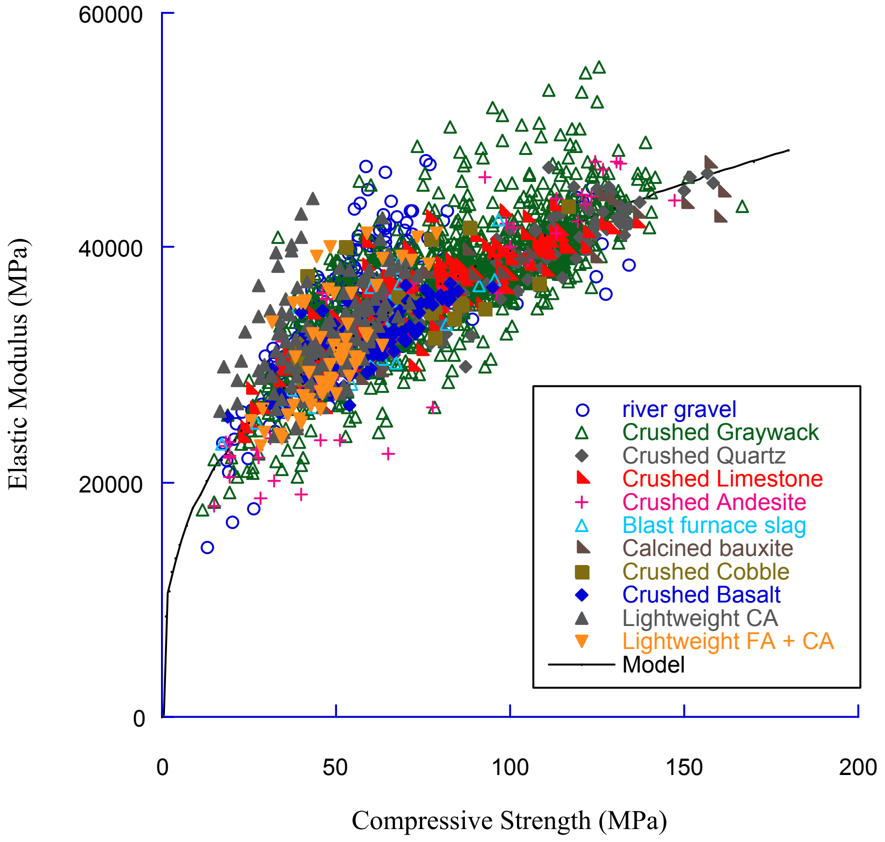
- Great care should be taken if using well-established equations developed for normal-strength concrete to estimate the elastic modulus of high-strength concrete. Extrapolation beyond the validity of the equations often leads to overestimation of the elastic modulus.

Elastic Modulus

- for normal weight concrete with 21 MPa < fc < 83 MPa
- where Ec is the elastic modulus of concrete, fc the compressive strength.

$$E_c = 3320 \sqrt{f_c} + 6900 \text{ MPa}$$

Data from Tomosawa and Noguchi



Chemical and Autogeneous shrinkage

- During hydration of the cement paste in a closed system, the volume of the hydration products, , is less than the sum of the volume of water and the volume of cement that is hydrated. This leads to chemical shrinkage whose magnitude can be expressed by

$$\varepsilon_{ch} = \frac{\left(V_c + V_w\right) - V_h}{V_{ci} + V_{wi}}$$

where and are the current and initial volume of cement, and and are the current and initial volume of water, respectively.

Early Volume Change

- Before setting, the chemical shrinkage is not constrained and, therefore, it will induce shrinkage of the same magnitude in the cement paste. As a rigid network of hydration products starts to develop, the values of the chemical shrinkage and that of the measured shrinkage in the cement paste start to diverge, since the rigidity of the paste restrains the deformation.

Definition of the autogenous shrinkage according to the Japanese Concrete Institute

- *macroscopic volume reduction of cementitious materials when cement hydrates after initial setting. Autogenous shrinkage does not include volume change due to loss or ingress of substances, temperature variation, and application of an external force and restraint*.

Concerns with the use of HSC (1)

- The lower modulus predicted by design codes.
- (note, not a problem anymore since most codes now have adequate equations)

Concerns with the use of HSC (2)

- The reported decrease of strength over time.

Concerns with the use of HSC (3)

- Fire resistance

Concerns with the use of HSC (4)

- Is AE necessary for HSC?

Examples of application

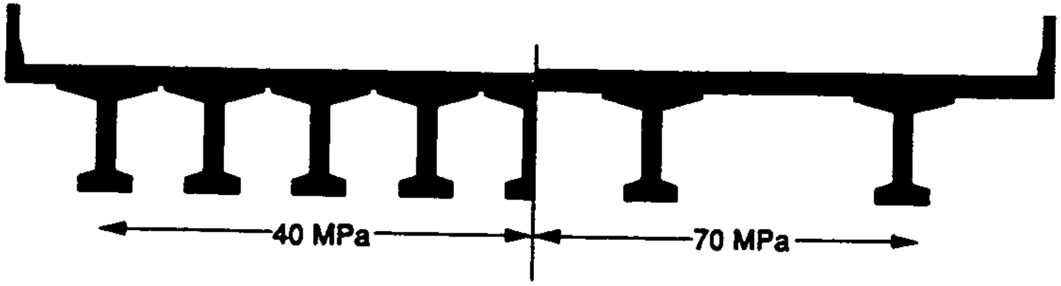
The bridge constructed in Joigny used concrete with 60 MPa instead of concrete with 35 Mpa. The volume of concrete reduced 30%

Examples of application

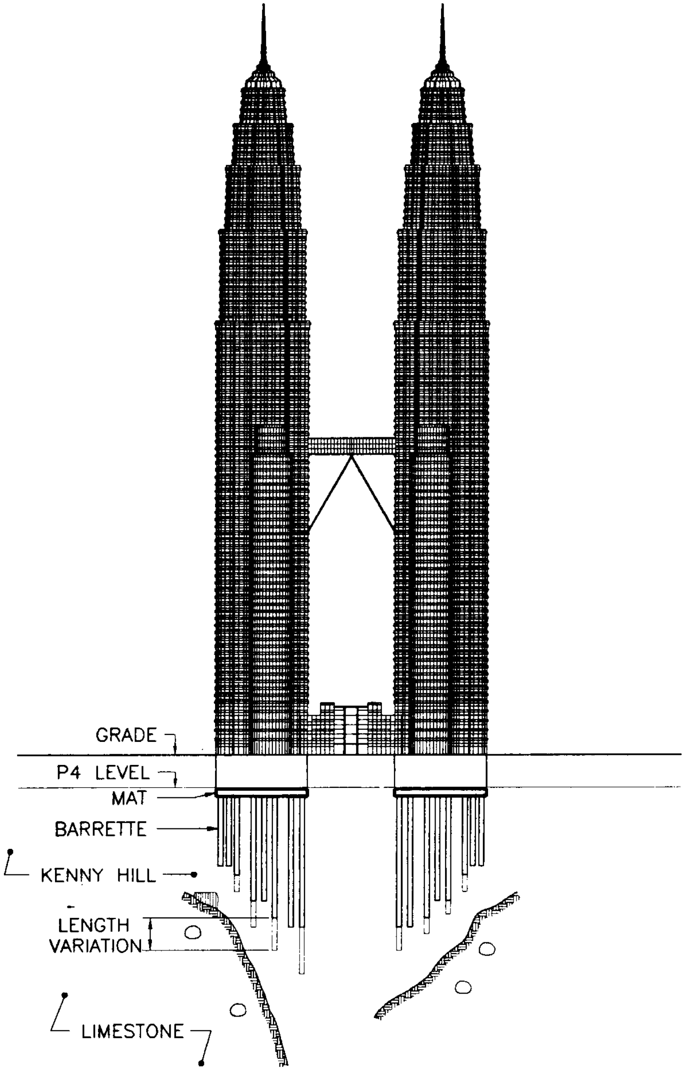
- Prof. Zia has shown that for 29-m spans with 80 Mpa concrete instead of 40 Mpa allow a 17% increase in span.

Examples of application

- Jobse has demonstrated that by increasing the compressive strength of concrete from 40 Mpa to 70 Mpa the number of supports could be reduced from nine to four



Petronas Towers



Pertronas Towers

- in Kuala Lumpur (Malasia)
- 450 m high
- 40-80 Mpa concrete
- Local workers

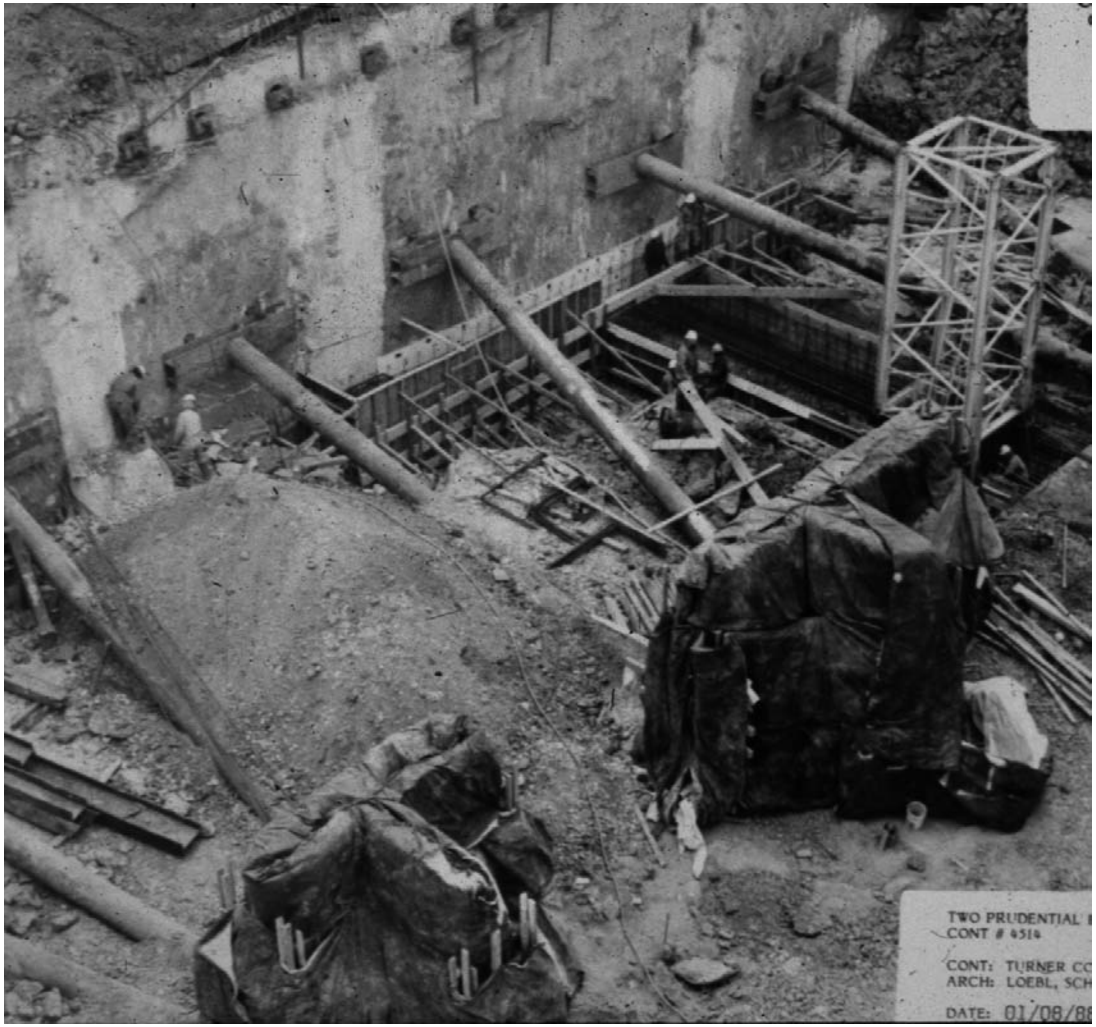
Advantages of using HSC in the Petronas Towers

- Structural Economy
- Efficient method of concrete placement
- Simplified construction joints
- Reduced vibration due to high wind

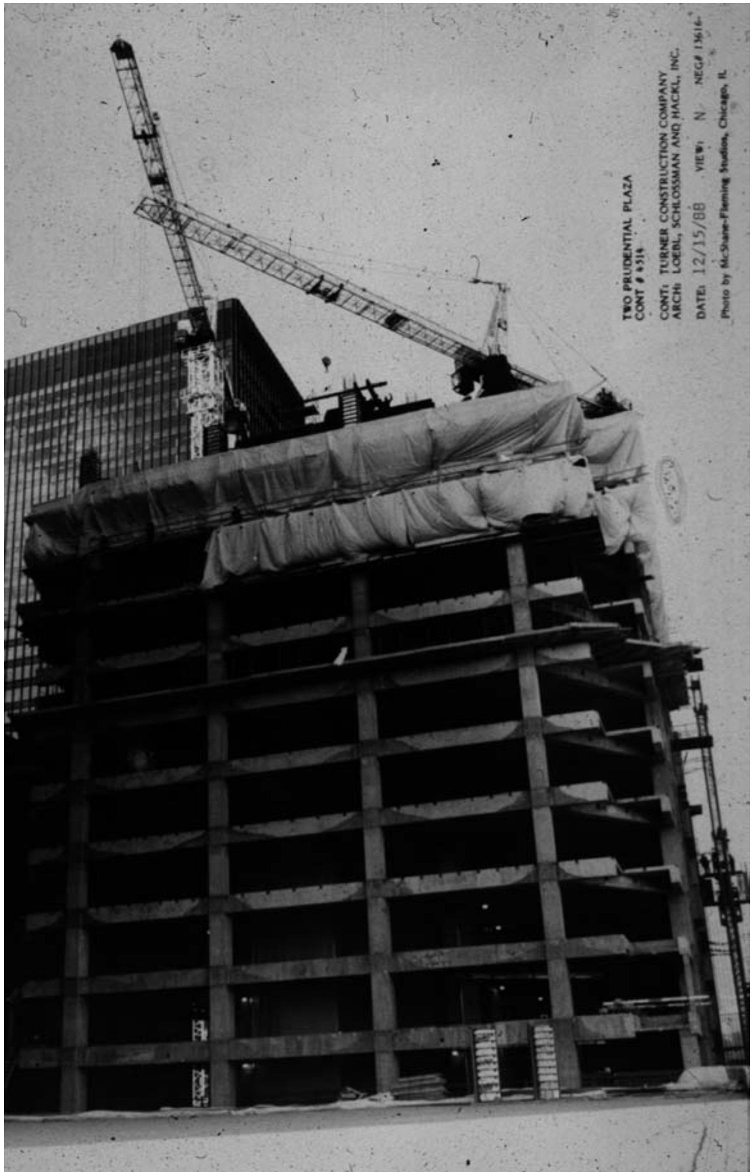
Special considerations used in Petronas Towers

- Complete study of creep and shrinkage
- Detailed analysis of wind effect on the structures. Note that the damping of concrete is twice as much as of steel

Construction Stage: Jan.



Construction Stage: Dez.



Construction Stage: March

Construction Stage: June