HIGH STRENGTH CONCRETE CONTAINING SILICA FUME AND METAKAOLIN

By

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ABSTRACT

The effect of silica fume (SF) and metakaolin (MK) on properties of high strength concrete mixes containing 0%, 10% and 15% silica fume and metakaolin as partial replacement of cement has been investigated. Experimental studies have been conducted to determine the influence of both mineral admixtures on the workability, strength development, surface hardness, porosity and permeability of high strength concrete. The slump, compacting factor, plastic density, compressive strength, Rebound number, ultrasonic pulse velocity, porosity and permeability tests were performed. The specimens were cured in water for periods varying from 1, 3, 7, 28 to 56 days before testing. It was observed that the specimens with 15% silica fume had the highest compressive strength, ultrasonic pulse velocity, Rebound number, lowest porosity and permeability at the age of 56 days. Whereas, the specimens with metakaolin had the compressive strength, ultrasonic pulse velocity, Rebound number lower than the specimens with silica fume but porosity and permeability higher than specimens with silica fume. The inclusion of mineral admixtures reduced the workability of concrete mixes. Nevertheless, it can be concluded that the mineral admixtures generally improved the compressive strength, ultrasonic pulse velocity, surface hardness and durability of high strength concrete.

ABSTRAK

Kajian terhadap kesan silica fume dan metakaolin pada sifat-sifat campuran konkrit kekuatan tinggi yang mengandungi 0%, 10% dan 15% silica fume serta metakaolin sebagai sebahagian penggantian terhadap simen Portland biasa. Penyelidikan secara eksperimen telah dijalankan untuk menentukan pengaruhan kedua-dua mineral tambahan terhadap kebolehkerjaan, perkembangan kekuatan, kekerasan permukaan, keliangan dan kebolehtelapan konkrit kekuatan tinggi. Ujian-ujian penurunan, faktor pemadatan, ketumpatan plastik, kekuatan mampatan, nombor Rebound, halaju dedenyut ultrasonik, keliangan dan kebolehtelapan telah dijalankan. Spesimen-spesimen telah diawet dalam air pada masa yang terdiri daripada 1, 3, 7, 28 sehingga 56 hari sebelum diuji. Diperhatikan bahawa spesimen yang mengandungi 15% silica fume sebagai penggantian sebahagian simen Portland biasa mempunyai peningkatan tertinggi dalam kekuatan mampatan, halaju dedenyut ultrasonik, nombor Rebound, penurunan keliangan dan kebolehtelapan pada umur konkrit 56 hari. Manakala, spesimen-spesimen yang mengandungi metakaolin mempunyai kekuatan mampatan, halaju dedenyut ultrasonik dan nombor Rebound yang lebih rendah daripada konkrit yang mengandungi silica fume serta keliangan dan kebolehtelapan yang lebih tinggi berbanding dengan konkrit yang mengandungi silica fume. Selain itu, pencampuran mineral tambahan telah menurunkan kebolehkerjaan campuran konkrit. Walau bagaimanapun, secara umumnya, boleh disimpulkan penambahan mineral tambahan dapat meningkatkan kekuatan mampatan, halaju dedenyut ultrasonik, kekerasan permukaan dan ketahanlasakan konkrit kekuatan tinggi.

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CHAPTER 1

INTRODUCTION

High strength concretes provide the civil and structural engineer with improved workability and strength, more durable concrete and improved structural characteristics. Therefore, high strength concrete is be coming widely used throughout the world in tall buildings, offshore structures, bridges, pavements, precast structural elements, piles, etc which are designed for long service life. In North America, Two Union square, Seattle in Chicago which was built in 1988 has a 19000 psi (131 MPa) compressive strength. Then, in Asia, Ootannabe Railway Bridge in Japan has 11400 psi (79 MPa) compressive strength and Petronas Twin Tower in Malaysia has a compressive strength of 80 MPa. Therefore, the use high strength concrete has been increasing in many parts of the world.

The developments in mineral admixtures have made it possible to produce concretes with relatively much higher strengths. Presently, concretes with strengths at 80 to 112 MPa are being commercially produced. Most modern high strength concretes contain at least one supplementary cementing material such as fly ash, blast-furnace slag, metakaolin or silica fume. Very often, the fly ash or slag is used in conjunction with silica fume or metakaolin. However the strength potential especially the strength in early ages may be reduced in particular at higher replacement levels.

In modern concrete practice, it is essentially impossible to make high strength concrete at adequate workability in the field without the use of water reducing admixtures or superplasticizers. The production of high strength concrete necessitates the use of low water-binder ratio, typically in the range of 0.22 to 0.4. Therefore, the use of a water reducing admixture or superplasticizers is necessary to obtain the low water-binder ratio and at the same time to give adequate workability. Actually, different water reducing admixture or superplasticizers will behave quite differently with different cements. Thus, some cement will simply be found to be incompatible with certain water reducing admixtures or superplasticizers.

There are some agreements that concrete with design compressive strength at 28 days over 50 MPa is defined as high strength concrete. In North American practice, high strength concrete is usually considered to be a concrete with 28-day compressive strength of at least 6000 psi (42 MPa). Then, in a CEB-FIB state-of-the-art Report on High Strength Concrete (1990), it is defined as concrete having a minimum 28-day compressive strength of 8700 psi (60 MPa). However, ACI committee 363 defines a high strength concrete as concrete that has a specified compressive strength for design of 6000 psi (41 MPa) or greater. Clearly then, the definition of high strength concrete is relative; it depends upon both the period of time in question and the location. Basically, high strength concrete can be defined as concrete which meets the requirements of strength, durability, density, ductility and other parameters that cannot always be achieved simply by using only conventional materials, normal mixing, placing and curing methods. Thus, high strength concrete is achieved primarily by carefully selecting, controlling and proportioning all ingredients.

For high strength concrete, however, all of the components of the concrete mixture are pushed to their critical limits. High strength concretes may be modeled as three-phase composite materials, the three phases being (i) the hardened cement paste; (ii) the aggregate and (iii) the interfacial zone between the hardened cement paste and the aggregate. These three phases must all be optimized, which means that each be considered explicitly in the design process.

In essence then, the proportioning of high strength concrete mixtures consists of three general steps: (1) selection of suitable ingredients which are cement, supplementary cementing materials (fly ash, silica fume, metakaolin and blast furnace slag), aggregates, water and chemical admixtures (superplasticizers), (2) determination of the relative quantities of these materials in order to produce as economical as possible, a concrete that has the desired rheological properties, strength and durability, (3) careful quality control of every phase of the concrete making process.

1.1 Problem Statement

In Malaysia, the utilization of high strength concrete has just initiated especially in high rise buildings and bridges. Thus, it is important to investigate the effect of mineral admixtures on the physical and mechanical properties of high strength concrete because the application of high strength and high performance concrete is important due to the rapid developing trend of the construction and concrete industry in Malaysia. It is generally accepted that the use of mineral admixtures could enhance the properties and performance of concrete.

In addition, the sources of mineral admixtures or the sources of raw materials for producing mineral admixtures such as fly ash, ground granulated blast-furnace slag, rice husk ash and metakaolin are readily available. Therefore, it is important to gather as much data and information as possible on the production and properties of high strength concrete in Malaysia, in particular those utilizing locally available mineral admixtures.

1.2 Objective

The objective of this study is to produce high strength concrete using ordinary Portland cement as well as combination of ordinary Portland cement with silica fume and metakaolin. The influence of each mineral admixture on the properties of high strength concrete in the fresh and hardened states is studied. Thus, the main objectives of this study are:

(i) To investigate the influence of silica fume and metakaolin on the workability of high strength concrete.

(ii) To investigate the influence of silica fume and metakaolin on the properties of harden concrete, in particular, strength, porosity, water absorption and permeability.

1.3 Scope

In order to achieve the objectives of the study, five concrete mixes were prepared which were a control mix, concretes with 10% and 15% silica fume as partial cement replacement, concretes with 10% and 15% metakaolin as partial cement replacement.

The properties of the fresh concrete investigated were workability and plastic density. The slump test and the compacting factor test were used to assess the workability of fresh concrete while the method for determination of density of compacted fresh concrete was applied to determine the plastic density of the fresh concrete. The dimensions of the cubes are 100mm x 100 mm x 100 mm and prepared for the compressive strength test, Rebound hammer test and ultrasonic pulse velocity test. In total, 75 cubes were prepared and for each mix, three cubes were tested at the ages of 1, 3, 7, 28 and 56 days testing age. All cubes were cured in the water

The gas permeability apparatus, the vacuum saturation apparatus were used to investigate the permeability and porosity of the hardened concrete, respectively. Cored samples were used for the determination of permeability and porosity. In total, 100 cores were prepared with dimensions of 50mm in diameter and 40 mm height. As in the case of strength, the cores were also tested on the ages of 1, 3, 7, 28 and 56 days with four cores prepared for each testing age.

CHAPTER 2

LITERATURE REVIEW

2.1 Selection of Materials

In order to produce high strength concrete as economically as possible, a concrete that has the desired rheological properties, strength and durability, it is necessary to get the maximum performance out of all of the materials involved in producing high strength concrete. Particularly when attempting to make high strength concrete, any material incompatibilities will be highly detrimental to the finished product. Thus, the design of any mix proportion must involve extensive testing of trial mixes.

2.2 Mix Proportions for High Strength Concrete

Only a few mix design methods for high strength concrete have been developed to date. Most commonly, purely empirical procedures based on trial mixtures are used. For instance, according to the Canadian Portland Cement Association, 'the trial mix approach is best for selecting proportions for high strength concrete'. Thus, much work remains to be done before any mix proportioning method for high strength concrete becomes as universally accepted. However, there are some general guidelines to determine the mix proportion of high strength concrete.

Selecting the proportions of high strength concrete needs more attention and consideration because every properties of the material will affect the properties of high strength concrete. Normally, the proportioning of high strength concrete mixtures consist not only ordinary Portland cement, coarse aggregates, fine aggregates and low water-binder ratio, but also mineral admixtures such as fly ash, ground granulated blast furnace slag, silica fume and metakaolin and chemical admixtures such as superplasticizers. There are some basic concepts that need to be understood for producing high strength concrete.

2.2.1 Ordinary Portland cement

Ordinary Portland cement is admirably suitable for use in general concrete construction when there is no exposure to sulphates in the soil or in ground water. The specification for this cement is given in BS 12: 1978. High strength concretes have been produced successfully using cements meeting the ASTM Standard Specification C150 for Types I, II and III Portland cements.

Generally, while producing high strength concrete, there are two different requirements that any cement must meet: (i) it must develop the appropriate strength; and (ii) it must exhibit the appropriate rheological behavior. Thus, the chemical and physical properties of cement used to produce the high strength concrete must meet the requirements. However, cements of nominally the same type will have quite different rheological and strength characteristics, particularly when used in combination with chemical admixtures and supplementary cementing materials. Consequently, when choosing ordinary Portland cements for use in high strength concrete, it is necessary to look carefully at the cement fineness and chemistry.

High strength concrete mixtures normally will have high cementitious materials content (415 to 650 kg/m^3) in comparison to normal strength concrete. There is some recommendation that the cementitious material content should not be more than 650 kg/m^3 because it will increase the heat of hydration and possibly causes higher shrinkage leading to the potential for cracking (CIP 33-NRCMA, 2001).

2.2.1.1 Fineness

Basically, increasing the fineness of the ordinary Portland cement will increase the early strength of the concrete because the higher surface area in contact with water will lead to a more rapid hydration. However, too high a fineness may lead to rheological problems, since the greater amount of reaction at early ages, by the way the formation of ettringite, will cause a higher rate of slump loss. Finer cement could also lead to alkali-aggregate reaction and exhibiting a higher shrinkage and a greater potential for cracking. Most cement used to produce high strength concrete have Blaine finenesses that are in the range of 300 to 400 m^2/kg, while the finenesses of Type III cements (high strength concrete) are in range of 450 m^2/kg. However, the types of cement used to produce high strength concrete are depending on the designers.

2.2.1.2 Chemical Composition of Cement

Normally, there are four components which are regarded as the major constituents of cement; they are listed in Table 2.1 together with their abbreviated symbols. Table 2.2 shows the approximate Oxide Composition of Portland Cement

Table 2.1: Main compounds in ordinary Portland cement (Neville and Brooks, 1993)

Name of compound	Oxide composition	Abbreviation
Tricalcium silicate	$3CaO.SiO_2$	C_3S
Dicalcium silicate	$2CaO.SiO_2$	C_2S
Tricalcium aluminate	$3CaO.Al_2O_3$	C_3A
Tetracalcium aluminoferrite	$4CaO.Al_2O_3.Fe_2O_3$	C_4AF

Table 2.2: Approximate oxide composition of Portland cement (Neville and Brooks, 1993)

Oxide	Composition (mass %)
Lime (CaO)	60-67
Silica (SiO_2)	17-25
Alumina (Al_2O_3)	3-8
Iron Oxide (Fe_2O_3)	0.5-6.0
Magnesia (MgO)	0.1-4.5
Alkalies ($Na_2O + K_2O$)	0.5-1.3
Titania (TiO_2)	0.1-0.4
Phosphorus (P_2O_5)	0.1-0.2
Gypsum (express as SO_3)	1-3

The presence of C_3A in cement generally leads to rapid loss of flow in the fresh concrete and thus high C_3A contents should be avoided in cements used for high strength concrete. Whereas, the silicates, C_3S and C_2S are the most important compounds, which are responsible for the strength of hydrated cement paste. Therefore, the chemical composition of the cements also affects the properties of cement to produce high strength concrete.

2.2.2 Aggregates

Aggregates play an important role on the properties of concrete, including rheological properties of fresh concrete mix; mechanical behavior and durability of hardened concrete. Aggregates should be strong and durable. Furthermore, the aggregate properties that are most important with regard to high strength concrete are particle shape, particle size distribution, mechanical properties of the aggregate particles and possible chemical reactions between the paste-aggregate interfaces which may affect the bond. The quality of coarse aggregate has a significant effect on the compressive strength of high strength concrete (Beshr *et. al*, 2002).

In ordinary concrete, the strength of the aggregates is rarely considered. However, in the case of high strength concrete, the aggregates may well become the strength limiting factor. Also, since it is necessary to maintain a low water-binder ratio to achieve high strength, the aggregate grading must be very tightly controlled. Thus, they need not necessarily be hard but need to be compatible to provide the stiffness and strength of high strength concrete.

2.2.2.1 Coarse Aggregate

For high strength concrete, the coarse aggregate particles themselves must be strong. A number of different rock types have been used to make high strength concrete; which include limestone, dolomite, granite, andesite and diabase. It has been suggested that in most cases the aggregate strength itself is not usually the limiting factor in high strength concrete; rather, it is the strength of the cement-aggregate bond. The reason is aggregates that may be susceptible to alkali-aggregate reaction and the deleterious effects may lead to expansion, cracking and disruption of the cement paste (pop-outs).

For both strength and rheological considerations, the coarse aggregate particles should be roughly equal-dimensional; either crushed rock or natural gravels, particularly if they are of glacial origin, are suitable. Flat or elongated particles must be avoided because they are inherently weak and lead to harsh mixes. Moreover, it is important to ensure that the aggregate is clean because a layer of silt or clay will reduce the cement-aggregate bond strength, in addition to increase the water demand. Furthermore, the aggregates should not be highly polished because this too will reduce the cement-aggregate bond. The quality of coarse aggregate has a significant effect on the compressive strength and modulus of elasticity of high strength concrete (Beshr *et. al*, 2002). Therefore, the properties of coarse aggregate play an important role in the production of high strength concrete.

Normally, a smaller maximum size coarse aggregate is used for producing high strength concrete because smaller size will improve the workability of concrete. Generally, the average diameter of coarse aggregate used to produce high strength concrete is 10-12 mm (Mehta and Aitcin, 1990). However, the size of coarse aggregate is depending on the designers.

2.2.2.2 Fine Aggregate

The sand or fine aggregate should consist of smooth rounded particles to reduce the water demand. Normally, the fine aggregate grading should conform to the limits established by the British or Malaysia standard for normal strength concrete. However, the ACI is recommending that the grading should lie on the coarser side of these limits and a fineness modulus of 3.0 or greater for fine aggregate in order to reduce the water requirements and to improve the workability. Of course, the sand too must be free of silt or clay particles.

2.2.3 Mineral Admixtures

Mineral admixtures refer to finely divided materials, which possess pozzolanic or/and cementitious properties, when used as concrete ingredients. They can be used to replace part of cement, or as an additive to cement from 5% to 30% of weight of cement. In either case, they are normally incorporated to the batch shortly before or during mixing.

Pozzolanic materials are usually defined as materials which, though not cementitious in themselves, contain constituents which will combine with lime at ordinary temperatures in the presence of water to form stable insoluble compounds possessing cementing properties. There are also some finely divided and non-crystalline or poorly crystalline materials similar to pozzolan but containing sufficient calcium to form compounds which possess cementing properties after interaction with water. These materials can be classified as cementitious (Somayaji, 2001).

Normally, most of the high strength concretes contain at least one mineral admixture such as fly ash, blast furnace slag, silica fume or metakaolin. These additional mineral admixtures can improve the strength and durability of concrete. Basically, these mineral admixtures are very fine particles compared to ordinary Portland cement and refined microstructure that can enhance the quality and long-term performance of concrete.

2.2.3.1 Silica Fume

Silica fume is a by-product from the production of elemental silicon and ferro-silicon alloys. It usually contains more than 80% silica in non-crystalline or amorphous form and has a spherical shape with average particles size of 0.1µm. Furthermore, silica fume is also collected as a by-product in the production of other silicon alloys such as ferrochromium, forromaganese, ferromagnesium and calcium silicon (ACI committee 226, 1987).

Silica fume consists of very fine vitreous particles with a surface area of 20000 m^2/kg (21528 ft^2/Ib) when measured by nitrogen absorption technique and with particles approximately 100 times smaller than the average cement particle. Because of its extreme fineness and high silica content, silica fume is a highly reactive pozzolanic material which is suitable for use in cement and concrete industries particularly in the production of high strength concrete. Moreover, the inclusion of silica fume results in a finer pore size distribution of concrete and the ability of the fine particles of silica fume to act as filler improve the aggregate-cement paste interface. The main results of pozzolanic reactions are: lower heat liberation and strength development; lime-consuming activity and smaller pore size distribution (Mazloom *et. al*, 2003). Therefore, silica fume becomes essential as an additional mineral admixture to the concrete mix especially to achieve the required compressive strengths up to 80 MPa.

However, high surface area of silica fume can increase the water demand of the concrete mix. Thus, to optimize the benefits of silica fume, high range water reducers (superplasticizers) are used to maintain mixing water requirements at an acceptable level.

Normally, a very low content of silica fume (below 5% of total mass of cementitous material) does not lead to a high strength of concrete while a very high content of silica fume is only marginally beneficial than about 10%. The optimum dosage of silica fume for general; construction usually varies between 7% and 10% but in specialized situation up to 15% silica fume has been incorporated successfully in concrete.

2.2.3.2 Metakaolin

Metakaolin is a thermally activated alumino-silicate material with high pozzolanic activity. It is also an alternative to the use of silica fume as the supplementary cementing materials in producing high strength concrete. Metakaolin is quite useful in improving concrete quality, such as enhancing strength, shortening setting time, reducing autogeneous shrinkage, controlling alkali aggregate reaction, reducing risk of chloride-induced corrosion of embedded steel and improving the durability of concrete (Li *et. al,* 2002). Therefore, metakaolin is a promising supplementary cementing material for manufacturing high strength concrete.

The raw material for the manufacturing of metakaolin is kaolin clay. Kaolin is a fine, white, clay mineral that has been traditionally used to manufacture porcelain. Kaolin clays consist of kaolinite. Kaolinite is defined as a common mineral, hydrated aluminum disilicate $(Al_2Si_2O_59OH)_4$ (Advance cement technologies, 2001).

The process to produce the metakaolin is called dehydroxilization. This thermal activation of a mineral is also referred to as calcination. The temperature at which kaolinite loses water by dehydroxilization is in the range of 500-800°C. Beyond the temperature of dehydroxilization, kaolinite retains two-dimensional order in the crystal structure and the product is called metakaolin.

Its average particle size is smaller than the average cement particle. When mixes with the concrete, it will serve to fill the interstitial spaces between cement grains, thus physically tightening the particle arrangement.

2.2.4 Chemical Admixtures

In concrete technology, the term ‘chemical admixture’ is restricted to soluble substances excluding air entraining agents. Most chemical admixtures react with cement and normally added to concrete in small amounts, usually dissolved in the mixing water. The commonly used chemical admixtures are; water-reducers or plasticizers, superplasticizers, retarding admixtures, accelerating admixtures and air-entraining agents. In this research, a superplasticizer is used as the chemical admixture in the production of high strength concrete mixes.

2.2.4.1 Superplasticizers

In modern concrete practice, superplasticizer is essentially used to make high strength concrete at required workability in the field. Unfortunately, different superplasticizers will behave quite differently with different cements (even cements of nominally the same type). This is due in part to the variability in the minor components of the cement (which are not generally specified), and in part to the fact that the acceptance standards for superplasticizers themselves are not very tightly written. Thus, some cement will simply be found to be incompatible with certain superplasticizers (Mindess, 1994).

There are, basically, three principal types of superplasticizers: (i) lignosulfonate-based; (ii) polycondendensate of formaldehyde and melamine sulfonate and (iii) polycondensate of formaldehyde and naphthalene sulfonate.

The main purpose of using superplasticizers is to produce flowing concrete with required slump or workability without altering the mix composition. The fluidity of cement paste increases with the increase in the dosage of superplasticizers (Li *et. al*, 2002). However, the dosage of superplasticizers should be added based on the required workability of high strength concrete. This is because when the dosage of superplasticizers reaches a certain amount, the fluidity of the paste does not increase significantly and the threshold dosage of the superplasticizers is called the saturation point. Moreover, superplasticizers have some effect of retarding the setting of mixes if used over the threshold dosage. Therefore, the ability of superplasticizers to increase the slump of concrete depends on such factors as the type, dosage and time of addition of superplasticizers, water-cement ratio and the amount of cement.

Superplasticizers are linear polymers containing sulfonic acid groups attached to the polymer backbone at regular intervals. The sulfonic acid groups are responsible for neutralizing the surface charges on the cement particles and causing dispersion. Thus releasing the water tied up in the cement particle agglomerations and thereafter reducing the viscosity at the paste and concrete (Somayaji, 2001).

2.2.4.1.1 Superplasticizers dosage

There is no a priori way of determining the required superplasticizers dosage; it must be determined, in the end, by some sort of trial and error procedure. Basically, if strength is the primary criterion, then the mixes should work with the lowest water-cement ratio possible, and thus the highest superplasticizers dosage rate. However, if the rheological properties of the high strength concrete are very important, then the highest water-cement ratio consistent with the required strength should be used, with the superplasticizers dosage then adjusted to get the desired workability. In general, of course, some intermediate position must be found, so that the combination of strength and rheological properties can be optimized.

2.2.5 Water/cement ratio

For normal strength concretes, mix proportioning is based to a large extent on the water/cement ratio 'law'. For high strength concretes, although the aggregate strength or the strength of the cement-aggregate bond, are often the strength controlling factors, the role of the water-cement ratio also important. Increasing water-binder ratio resulted in a decrease in the compressive strength (Turkmen, 2003). Therefore, high strength concrete mixtures generally need to have a low water-cement ratio. It can be in the range of 0.22 to 0.40. These low water-cement ratios are only attainable with quite large doses of high range water reducing admixtures.

2.3 Behavior of Fresh Concrete

2.3.1 Workability

Workability of fresh concrete is an important factor to measure the ability of fresh concrete be properly compacted, transported, placed and finished sufficiently easily without segregation. Workability also can be defined as the amount of useful internal work necessary to produce full compaction. The useful internal work is a physical property of concrete and the work or energy required to overcome the internal friction between the individual particles in the concrete (Neville, 1981).

Silica fume is very fine particle sizes that cause some of the superplasticizer being adsorbed on its surface. Therefore, the high strength concrete mixes incorporating silica fume become sticky and decrease the bleeding of fresh concrete, in order to enhance workability. However, the superplasticizer dosages have to be adjusted to get the desired workability, in term of low water-binder ratio.

Metakaolin is a soft, high specific surface and very fine particle material. Thus, metakaolin can improve workability of concrete because metakaolin can easily absorb the water molecules to decrease the fluidity of concrete. Metakaolin degraded the fluidity under the condition of adding the same dosage of superplasticizer compared to control concrete (Li *et. al*, 2002). Therefore, metakaolin normally increase the water demand of concrete significantly.

Typically, silica fume and metakaolin can increase the water demand of concrete significantly. This is due to the much finer particle size of these materials in comparison to cement, higher surface area and greater water demand. Therefore, for concrete mixes with constant workability, the use of these mineral admixtures will reduce the workability.

Generally, there are three common methods to measure the workability, which are slump test, vebe time test and compacting factor test. The slump test is described in BS 1881: Part 102: 1983, compacting factor test is described in BS 1881: part 103: 1983 and vebe time test is covered by BS 1881: Part 104: 1983.

2.3.2 Setting time

Setting is the term used to describe the stiffening of the cement paste, although the definition of the stiffness of the paste which is considered set is somewhat arbitrary. Broadly speaking, setting refers to a change from a fluid to a rigid state. Setting time can vary dramatically depending on the application and the presence of set modifying admixtures and percentage of the paste composition of portland cement (Aquino *et. al.* 2001).

2.4 Behavior of Hardened Concrete

2.4.1 Compressive Strength

The compressive strength is perhaps the most important overall measure of quality because compressive strength is the common basis for design for most structures and directly related to the structure of hardened cement paste.

Presently, 28 days strengths of up to 12000 psi (84 MPa) are routinely obtainable. The Petronas Twin Tower in Malaysia is designed up to 28 days compressive strength of 11600 psi (80 MPa). Therefore, it is possible that the development of high strength concrete with compressive strength more than 80 MPa with the addition of supplementary cementing materials.

Silica fume containing amorphous silica content. Thus, silica fume can react with the hydrates of cement to form Calcium-Silicate-Hydrates (C-S-H) gel. The partial additional of ordinary Portland cement with silica fume reduces calcium hydroxide availability due to the pozzolanic reaction.

Addition of metakaolin in superplasticised concrete enhances the early strength of the hardened concrete. Metakaolin contains actively amorphous silicon dioxide and aluminum oxide; they can react with hydrates of cement to form C-S-H gel and calcium suphoaluminate (ettriginite, AFe). This reaction forms the framework of cement paste in the early hydration period. Besides that, metakaolin belongs to reactive mineral admixtures, which can improve the microstructure of the blended cement. The ultra-fine particles fill the voids in cement, which makes the microstructure of cement paste denser (Li *et. al*, 2002).

Actually hydrated ordinary Portland cement contain $Ca(OH)_2$, (CH) while hydrated. CH is released by cement clinker hydration. Moreover, CH often occurs in the form of crystal and produce interfaces (weak combination) inside the cement matrix. CH cannot provide strength to the cement paste, only after it was translated to C-S-H gel by pozzolanic reaction with active material. The secondary formed C-S-H gel improves the microstructure of cement paste matrix; therefore, the macroscopic property of cement is also improved (Li *et. al*, 2002). Thus, both silica fume and metakaolin can react with the calcium hydroxide, CH to form C-S-H making the microstructure denser and improve the compressive strength.

Furthermore, C-S-H has a tremendous specific surface, which produces a greater combination force inside the paste and it is a continuum structure (there is no interface). The more of CH consumed, the more C-S-H is formed and the higher strength of cement can produce (Li and Ding, 2002). So, both silica fume and metakaolin can form the secondary C-S-H gel inside the cement paste and thus can improve the compressive strength of concrete.

2.4.2 Porosity

Porosity is a kind of properties of the layer of concrete. Increase the water-cement ratio, increase in the capillarity coefficient and resulted in a decrease in compressive strength (Turkmen, 2003). Therefore, there was similar effect between water-cement ratio-compressive strength and water-cement ratio-porosity. High strength concrete consists of low water-cement ratio, so the porosity of concrete can reduce. Moreover, both silica fume and metakaolin can fill the voids and thus decrease the pores in the concrete. As silica fume content increases, the pore size distribution is shifted toward a finer distribution, the average pore size reduces and the porosity decreases (Mazloom *et. al,* 2003). Besides that, both silica fume and metakaolin can increase the degree of hydration because they are highly reactive pozzolanic material; as a result decrease the porosity of concrete.

However, high strength concrete containing metakaolin has the percentage of porosity higher than high strength concrete with additional of silica fume. This is because metakaolin particles lead to acceleration of cement hydration and easily adsorb the water in early age of hydration. Besides that, the inclusion of metakaolin can refine the pore structure and a slight increase in porosity of paste (Khatib *et. al*, 2003).

2.4.3 Shrinkage

Shrinkage is the decrease of concrete volume with time. This decrease is due to changes in the moisture content of the concrete and physio chemical changes, which occur without stress attributable to actions external to the concrete. Shrinkage is primarily a function of the paste, but is significantly influenced by the stiffness of the course aggregate.

The aggregate acts to restrain the shrinkage of cement paste; hence high strength concrete with higher aggregate content exhibits smaller shrinkage. In addition, high strength concrete with aggregates of higher modulus of elastic or of rougher surface is more resistant to the shrinkage process. Moreover, high strength concrete contain a low water-cement ratio and as a result a lower the shrinkage. The higher the water-cement ratio is, the higher the shrinkage. This occurs due to two interrelated effects. As water-cement ratio increases, paste strength and stiffness decrease; and as water content increase, shrinkage potential increases.

Admixture effect varies for different types of admixtures. Any material which substantially changes the pore structure of the paste will affect the shrinkage characteristics of the concrete. In general, as pore refinement is enhanced shrinkage is increased (Larrard, 1990).

Silica fume will contribute to strength at an earlier age than other pozzolans but may still increase shrinkage due to pore refinement. Meanwhile, silica fume did not affect the total shrinkage but as the proportion of silica fume increased, the autogenous shrinkage of high-strength concrete increased and its drying shrinkage decreased (Mazloom *et. al,* 2003). Then, the effect of silica fume on autogenous shrinkage is based on the pore structure, pore size distribution of concrete and its pozzolanic reaction. So, at higher silica fume replacement levels, the greater part of the total shrinkage was contributed by autogenous shrinkage.

However, the effect of metakaolin reduces the total shrinkage as the level of replacement increases. The reduction in the total shrinkage can be partly attributed to the lower amount of evaporable water. The hydration and pozzolanic reaction of metakaolin used with a significant amount of the free water in the concrete mix. Metakaolin can reduce the autogenous shrinkage of high strength concrete than control concrete. Similar with the silica fume concrete, autogenous shrinkage influenced greater part of the total shrinkage in metakaolin concrete. Compared with the control concrete, the greater part of the total shrinkage of the metakaolin concretes is contributed by autogenous shrinkage and the drying shrinkage influenced smaller part of total shrinkage (Brooks *et. al*, 2001).

2.4.4 Creep

When a viscoelastic materials is subjected to a stress, from a time t_o, its strain, measured parallel to the axis of the stress, changes over time. This time dependent increase in strain of hardened concrete subjected to sustained stress is termed creep.

Creep is closely related to shrinkage and both phenomenons are related to the hydrated cement paste. As a rule, a concrete that is resistant to shrinkage also has a low creep potential. The principal parameter influencing the creep is the load intensity as a function of time; however, creep is also influenced by the composition of the concrete, the environmental conditions and the size of the specimen (Larrard *et. al*, 1992).

Silica fume can reduce the rate of creep because the volume of hydrates in high strength concrete is decreased as the level of silica fume replacement increased. Further more, high strength concrete containing silica fume has a low water-cement ratio and superplasticizers, this gives a reduced volume of the free water content, as a result it reduces creep. However, the general effect of silica fume inclusion is to decrease moisture movement due to the filler effect of silica fume. Thus, as the level of silica fume replacement increased, the total creep and basic creep of concrete were decreased (Mazloom *et. al*, 2003).

As in the case of silica fume, the inclusion of metakaolin also can reduce the creep. The reduction in creep could be attributed to a denser pore structure, stronger paste matrix and improved paste aggregate interface of the metakaolin concrete mixtures. This is because the formations of additional hydrate phases from secondary pozzolanic reaction of metakaolin and its filler effect. Moreover, the pozzolanic reaction of metakaolin with calcium hydroxide leads to the acceleration in cement hydration. Furthermore, the refined pore structure could influence the movement of water which is affect the initial creep. Therefore, metakaolin is suitable to reduce the creep of concrete. Besides that, at higher replacement levels of metakaolin, both of the total creep and basic creep of concrete were reduced (Brooks *et. al*, 2001).