Effects of Using Waste Glass with Different Particle Sizes to Replace Sand in Pre-cast Concrete Blocks

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By

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Declaration

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LEE Gerry

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Abstract

In Hong Kong, majority of waste glass is not being recycled and disposed to landfills directly which causes a serious environmental problem to the society. It has been proved that using recycled glass as a material in concrete is a feasible way to solve the problem. Previous studies found that the particle size of recycled glass cullet would affect the properties and ASR resistance of concrete. Moreover, most of the previous studies focused on wet-mixed concrete but few studies focused on dry-mixed concrete. For these reasons, this study aims to investigate the effects of different replacement percentages and particle size distribution of recycled fine glass (FG) aggregates on the properties of dry-mixed and wet-mixed concrete blocks, and the alkali-silica reaction (ASR) resistance of dry-mixed and wet-mixed mortar bars.

All the block mixtures were proportioned with a fixed total aggregate/cement ratio of 4 and 50% of the total aggregate was fine aggregate. A total of 17 concrete block mixes, including a control (0% of glass) mix, were produced using four different particle sizes of FG (Un-sieved, <2.36mm, <1.18mm and <600μm) as replacements of sand. The replacement ratios were 25%, 50%, 75% and 100%. Properties such as packing volume ratio, hardened density and water absorption, as well as the effects of air and water curing upon 7 and 28-day compressive strength were studied.

All concrete blocks (dry-mixed and wet-mixed) containing FG showed higher water absorption and lower hardened density than the control. The effect was more pronounced for FG with particle size less than 600μm. Slight reductions in compressive strength were

observed with the use of coarser FG, while significant increases in compressive strength occurred when the particle size of FG was reduced to less than 600μm. This indicates that finer FG exhibited appreciable pozzolanic reactivity.

For dry-mixed concrete blocks, the results show that the water demand for mixing and fabrication increased with decreasing fineness modulus of the fine aggregate.

The effects of different particle size of FG on the properties of dry-mixed and wet-mixed concrete blocks were similar. The effect of water curing increase on compressive strength of the wet-mixed concrete was larger than that of the dry-mixed concrete blocks.

The ASR expansion test results reveal that ASR expansion is reduced with reducing particle size of glass used. For a given mix proportions, the dry-mixed method led to lower ASR expansion (by up to 44% in average) as compared with the wet-mixed method. SEM images reflected that no cracks were observed in the dry-mixed mortar bars but cracks were observed in the wet mixed mortar bars after the ASR expansion test. The addition of PFA and MK (5-15% by mass of aggregate) led to the lower ASR expansion of the mortars. The positive effects of PFA and MK in reducing ASR expansion make these materials as potential ASR suppressants.

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Chapter 1 – Introduction

1.1. Background

In Hong Kong, about 300 tonnes of waste glass are generated everyday which accounts for about 2.5% of municipal solid waste stream in 2007. The rate of recycling and recovery of waste glass is about 1% which is the lowest among other developed countries. This extremely low recycling rate is due to the local beverage manufacturers have moved their bottling plants outside Hong Kong to the other countries. They are not willing to receive the post-consumer bottle wastes due to the high transportation cost. Secondly, the raw materials for glass such as silica (SiO_2), potash (K_2CO_3) and lime (CaO) are abundant, widespread and cheap in the world. There is no significant benefit for industries to collect and recycle glass wastes. Moreover, the process of collecting glass wastes is too complicated and expensive which included complicated procedures like color sorting and cleaning of glass waste. (EPD, 2007; EPD, 2008) It seems that Hong Kong does not suited for traditional methods of glass recycling and should look for other solutions.

Besides, the shortage of river sand is now posting a threat to the construction industriy in Hong Kong. The remedy for such situation is developing new sources of fine aggregates to replace sand. Using crushed glass waste as a fine aggregate to replace natural sand is a good possible alternative. It conserves the natural resources, reusing the waste and save the space for landfilling of waste.

Many studies have been conducted and proven that it is fashine to use recycled glass wastes as aggregate or cement replacement in concrete for constructions. (Shao et al., 2000; Byars et al., 2004; Shi and Zheng, 2007; Lam, 2007)

In Hong Kong, a local construction material production company is producing by using recycled crushed glass bottle waste. Glass bottles are washed and crushed mechanically and mixed with concrete materials to produce concrete blocks.

But it is necessary to conduct experiments to assess the effect of using different size of recycled fine glass in concrete blocks on how it influences its physical and durability properties.

1.2. Objectives

The objectives of this study were to determine the effects of recycled fine glass (FG) on the properties of wet-mixed and dry-mixed concrete blocks and ASR resistance of wet-mixed/dry-mixed mortar bars, the details are as follow:

- Investigate the effect of different sizes of FG on the physical, fresh and hardened properties of dry-mixed concrete blocks.
- Investigate the effect of different sizes of FG on the physical, fresh and hardened properties of wet-mixed concrete blocks.
- Investigate the effect of different sizes of FG on the alkali-silica reaction (ASR) resistance on dry-mixed and wet-mixed mortar bars.

- Comparison of the properties of dry-mixed and wet-mixed concrete blocks that containing FG, and the ASR expansion of dry-mixed and wet-mixed mortar bars that containing FG
- Investigate the effects of adding pulverized fly ash (PFA) and metakaolin (MK) on the ASR resistance of FG mortar bars.

1.3. Scope

The following tasks were carried out to fulfill the objectives of this project:

- Dry-mixed concrete blocks specimens were prepared with different nominal sizes of FG replacing natural fine sand with different replacement proportions by 25%, 50%, 75% and 100%.
- Wet-mixed concrete blocks specimens were prepared with different nominal sizes of FG replacing natural fine sand with different replacement proportions by 25%, 50%, 75% and 100%.
- Dry-mixed and wet-mixed concrete blocks specimens were prepared with different nominal size of recycled fine glass (FG) totally replacing natural fine sand.
- Dry-mixed mortar bars with different difference size of recycled fine glass (FG) were prepared with the addition of pulverized fly ash (PFA) and metakaolin (MK) for ASR expansion test.
- Computer modeling of packing volume ratio of aggregate, slump, hardened density, water absorption, compressive strength test were conducted to determine the properties of concrete blocks

- Alkali-silica reaction (ASR) expansion test (according to ASTM C1260), flexural strength test, scanning electronic microscope (SEM) analysis were conducted to assess ASR resistance of mortar bars

1.4. Arrangement of the Thesis

This thesis deals with the use of recycled fine glass in concrete blocks and mortar bars. A brief description of the different chapters is given below.

- ***Chapter 1*** is an introductory chapter that presents the background to the topic, the objective and scope of the thesis.
- ***Chapter 2*** reviews the literatures related to the topic of the thesis. It presents the recent development of recycling of glass waste at Hong Kong and other countries; the research findings about the determining factors on the properties of concrete; the research findings related to the use of waste glass in concrete; background, usage and properties about precast concrete blocks and the needs on further investigate the properties and durability of concrete blocks incorporate with waste glass.
- ***Chapter 3*** presents the methodology of the research, including the introduction of materials for concrete mixing, procedures of specimen preparation and testing methods.
- ***In Chapter 4,*** the effects of different particle size of FG and different content of FG on the properties of dry-mixed concrete blocks are presented. The relationship between the fineness modulus of fine aggregate and water demand of concrete mixes, the effects of different particle size of FG on the packing volume ratio of aggregates,

hardened density, water absorption, compressive strength and the effect of water curing on compressive strength of concrete blocks, are reported and discussed.

- ***In Chapter 5,*** the effects of different particle size of FG and different content of FG on the properties of wet-mixed concrete blocks are presented. The relationship between the fineness modulus of fine aggregate and demand of superplasticizer for concrete mixing, hardened density, water absorption, compressive strength and the effect of water curing on compressive strength of concrete blocks, are reported and discussed.
- ***In Chapter 6,*** the effects of different particle size of FG on the alkali-silica reaction (ASR) resistance of wet-mixed and dry-mixed mortar bars are presented. The relationship between particle size of FG and the expansion of mortar bar under ASR expansion test is reported and discussed. The results of flexural strength test, SEM analysis are also presented to support the findings on ASR expansion test.
- ***In Chapter 7,*** based on the result and discussion of chapter 4,5 and 6, the comparison on the effects of different size of FG on the properties of the dry-mixed and wet-mixed concrete blocks, and the ASR expansion of dry-mixed and wet-mixed mortar bars are made.
- ***In Chapter 8,*** the general conclusions obtained for experimental work are presented. The recommendations for the mix design of dry-mixed and wet-mixed concrete block, and for reduction of ASR expansion and for further works, are presented.

1.5. Research Significance

In the recent decade, there were lots of researches conducted regarding to the use of recycled crushed glass wastes in wet-mixed concrete production. There is a need to investigate the factor influencing on the properties of concrete incorporating with glass while particle size of glass may be a possible factor.

Also, most of the researches are focusing on wet-mixed concrete and only very few literatures are related to the use of recycled crushed glass waste in dry-mixed concrete. It is worth to compare the properties of dry-mixed and wet-mixed concrete that containing FG..

Moreover, it has been suggested that dry-mixed concrete could be an effective alternative solution to reduce ASR in concrete. It is worth to study the effects of different particles size of recycled glass were also evaluated ways to further reduce the ASR expansion by using different pozzolanic materials were compared.

Chapter 2 – Literature Review

2.1. Background

The management of waste glass is one of the major problems around the world especially in densely-populated cities. In Hong Kong, government data (EPD, 2007) showed that about 300 tonnes of glass waste is generated daily, however, the recovery rate is only about 1-2%. This situation may be due to the fact that no local glass manufacturing industry in Hong Kong to serve as a viable recycling outlet.

The traditional method of waste glass recycling requires high amount of energy to melt the waste glass and processes it to reproduce new glass containers and other glass related products. The collected waste glass is usually mixed colored and contaminated with dirts. The recycling process requires costly sorting procedures and removal of contaminants. Comparatively, mechanical recycling, for example, crushing the waste glass to a cullet form and used as aggregate in concrete, is a more economical way for waste glass recycling because it requires less energy, and less pre-recycling procedures, such as sorting and cleaning.

Studies on using crushed waste glass as aggregates for concrete production had been conducted since 1960s. (Pike et al., 1960; Schmidt and Saia, 1963) More researches have been conducted in the last decade due to the increase of waste disposal costs for waste glass and social concern on environmental issues in many countries. Many studies have demonstrated that it is feasible to use recycled glass wastes as aggregates or cement replacement in concrete for construction (Shao et al., 2000; Corinaldesi et al., 2005; Kou and Poon, 2009).

However, there is always a problem concerning the use of glass in concrete because of the possible alkali-silica reaction (ASR) of the silica-rich glass and the alkali in the pore solution of concrete. The problem can be partially solved by adding pozzolanic materials such as pulverized fly ash (PFA) and metakaolin (MK) into concrete. Besides, reduction of particle size to a very fine scale can also reduce the ASR expansion of concrete. (Jin et al., 2000)

In this chapter, firstly, the method of production of concrete and the major factors influencing the properties of concrete are discussed. Then, the properties of glass and the current situation on waste glass recycling are reviewed. Studies and findings on using waste glass as aggregate in concrete is also reported. Finally, effects of particle size of glass on ASR and pozzolanic reaction of concrete are discussed.

2.2. Production of Concrete and Major Factors Influencing the Properties of Concrete

2.2.1. Introduction

Concrete is a construction material composed of cement, coarse aggregates made of granite or other crushed rocks, fine aggregates such as sand, water and other chemicals like admixtures. It solidifies, hardened and gained strength after mixing with water and placement due to a chemical process which is known as hydration. (Stella, 1996)

In this section, method of production of concrete and the factors influencing the properties of concrete are discussed.

2.2.2. Method of production of concrete

Concrete is widely used in the construction industry. Different mixing methods may be applied for different usages. There are two major methods of concrete production, wet-mixing and dry/semi-dry-mixing methods which are described as follow;

Wet-mixing method

The wet-mixing method is also known as the conventional concrete casting method. The concrete mixture requires a sufficient water content or the addition of superplasticizer to provide workability and fluidity for compactio. Internal and external vibration is used to compact the mixture after placing in moulds. Throughout this process, most of the entrapped air voids of the concrete mixture are removed.

The desired finish and shape of concrete can be produced by using different shape of timber or steel moulds. Most of the void content in concrete can be removed by vibration. Segregation and bleeding may occur during the process of vibration which leads to inconsistence of concrete quality.

Concrete produced by wet-mixing method is used in structural concrete because higher strength of concrete can be produced for structural purpose.

Dry-mixing method

In the dry-mixing method, which is also called the semi-dry mix method, only a very small amount of water is added to the concrete mixture to provide sufficient cohesioness of the mixture but with zero workability. The semi-dry mixture is cast into steel/timber mould and compacted by a large compressive force for several seconds to pack the mixture and squeeze out the void content. The duration for compaction of concrete mixture is generally 4-7 seconds. The water requirement for the dry-mixing method is much lower comparing with that for the traditional wet mix method. The strength of the dry-mixed concrete is lower than that of the wet-mixed concrete while having the same cement/aggregate ratio since dry-mixed concrete has a higher void content than wet-mixed concrete. This void content can be reduced if an optimum duration and force for compaction during fabrication is applied. The advantage of using dry-mixing method to produce concrete blocks is that it can be demoulded immediately just after the compaction of the fresh concrete and the mould can be used again immediately. (Taylor, 1992)

Dry-mixing method is used for manufacturing of pre-cast concrete paving blocks and partition bricks because dry-mixing method is suitable for mass production that steel mould is able to be removed and used for next production immediately after compaction of concrete mixtures.

Dry-mixed concrete contains relatively more porosity than wet-mixed concrete due to the different compaction methods used. Dry-mixed concrete production is only suitable for small size precast elements such as concrete paving blocks (Figure 2.1).

Figure 2.1 : Dry-mixed concrete paving blocks

2.2.3. Major factors influencing the properties of concrete

Effects of shape and texture of aggregates

The sharp and texture of aggregates influence the strength of concrete directly. Several types of aggregates are classified according to BS 812, which include rounded, irregular, flaky, angular, elongated and flaky. They influence the degree of packing of particles in the concrete mixtures which also have a strong influence on the water requirement during mixing, and thus, has a significant influence on the strength of concrete. The smoothness of the aggregate influences the interfacial transition zone (ITZ) between the cement paste and the aggregates. The smoother the surface of aggregate, the weaker is the bond strength between cement paste and aggregates. In general, aggregate with rounded texture and rough surface is desirable to produce concrete with higher strength and better quality. (Erdoğan et al., 2008)

Effects of strength of aggregates

The compressive strength of concrete is directly related to the mechanical strength of the aggregate used. It is easy to understand that higher strength of aggregates would lead higher strength concrete.

Poon and Lam (2008) found that the compressive strength of concrete was directly proportional to the ten percent fine value of aggregates used. The compressive strength of concrete is increased from 45 to 85 MPa while the ten percent fine value of aggregate (included natural crushed granite and recycled crushed waste concrete) is increased from 100 to 160 kN.

Effects of chemical properties of aggregates

Most of the natural aggregate like granite contains reactive silica which may react with the alkalis in cement which is known as alkali-silica reaction (ASR) would lead to the expansion, cracking and damage of concrete.

The alkali-silica reaction (ASR) is a chemical reaction which occurs over time in concrete between the alkali and reactive non-crystalline silica, which is found in many common aggregates.

This reaction causes the expansion of the altered aggregate by the formation of a swelling alkali-silica gel. The amount of gel is increased in volume with water and exerts an expansive pressure inside the material, causing spalling of concrete and weakening of strength of the concrete.

Therefore, it causes serious expansion and cracking in concrete, resulting in critical structural problems that can even force the demolition of a particular structure.

The mechanism of ASR causing the deterioration of concrete is described as follows: Firstly, the alkali attacks the siliceous aggregate to convert it to viscous alkali-silica gel. Consumption of alkali by the reaction induces the dissolution of Ca^{2+} ions into the cement pore water and then react with the gel to convert it to hard calcium silicate hydrate. The penetrated alkaline solution converts the remaining siliceous minerals and water into bulky alkali-silica gel which results an expansive pressure in the aggregate and may lead to deterioration of concrete. (Ichikawa. and Miura, 2007)

The ASR deterioration can be reduced by adding of pozzolanic materials (PFA, MK and SF) in concrete. ASR expansion of concrete could be able to reduce with maximum 70% if 15% of pozzolanic materials were added to concrete by weight of cement. (Swamy, 1992, Zhu and Byars, 2004; Lam et al, 2007)

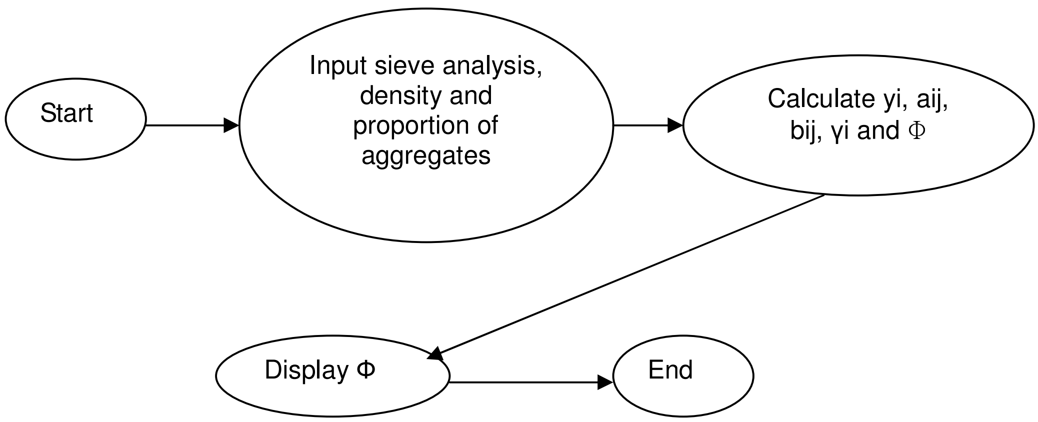
Effects of packing volume ratio of aggregates

The packing volume ratio of aggregates is the solid volume in a unit total volume. It depends on three main parameters: the size of grain, the shape of grains and the method of processing the packing. (Larrard, 1999) The higher value of packing volume ratio means that the aggregates are packed closer and less voids are produced, the higher would be the compressive strength of concrete.

The concept of aggregate packing was first noticed since Fuller and Thompson (1907) proposed the ideal grading curve. Less voids between aggregate particles, obtained as the grading curve of the aggregate particles, were close to the ideal grading curve.

With the evolvement of advanced computer technology in recent decades, various numerical models such as the Compressive Packing Model (CPM) have been developed to estimate the packing volume ratio of aggregates (Larrard and Thierry, 2002; Larrard, 1999). The CPM is based on the concept of virtual packing volume ratio and compaction index. The virtual packing volume ratio is defined as the maximum packing volume ratio achievable within a given mixture, each particle keeping its original shape and being placed one by one. The virtual packing volume ratio is also affected by the loosening and wall effects.

A computer programme model based on CPM theory proposed by Larrard F. de (1999) was developed and used to determine the theoretical packing volume ratio of the aggregates used for the block production (Lam, 2006).



The wall effect and loosening effect were calculated and according to the following equations:

$$a_{ij} = \sqrt{1-(1-d_j/d_i)^{1.02}} \text{ --(Eq 3.1)}$$

$$b_{ij} = 1-(1-d_i/d_j)^{1.50} \text{ ---(Eq 3.2)}$$

And the virtual packing volume ratio was calculated by the following equation.

$$\gamma_i = \frac{\beta_i}{1-\sum_{j=1}^{i-1}\left[1-\beta_i + b_{ij}\beta_i\left(1-1/\beta_j\right)\right]y_j - \sum_{j=i+1}^{n}\left[1-a_{ij}\beta_i/\beta_j\right]y_j} \text{ ----------------(Eq 3.3)}$$

The wall effect was not significant except the aggregate sized from 10 to 5mm. Therefore, βi was simplified into (1+1/K)Φ' and the value of K was 8.

β_i = Virtual packing volume ratio of a monodisperse fraction having a diameter equal to di

a $_{ij}$ = Parameter describing the loosening effect exerted by class j on the dominant class i

b $_{ij}$ = Parameter describing the wall effect exerted by class j on the dominant class i

$$y_i = \frac{\Phi_i}{\sum_{i=1}^{n}\Phi_i} \text{ ---(Eq 3.4)}$$

where the partial volume Φ are the volume occupied by each class in unit bulk volume of the granular mix.

The theoretical packing volume ratio, Φ, was determined by using Eq 3.3 and the implicit function (Eq 3.4).

$$K=\sum_{i=1}^{n}K_i=\sum_{i=1}^{n}\frac{\frac{y_i}{\beta_i}}{\frac{1}{\phi}-\frac{1}{\gamma_i}}$$ --(Eq3.5)

γ_i =Virtual packing volume ratio of polydisperse mix, when the I fraction is dominant

Φ =Actual packing volume ratio

K =Compaction index

β_i = Virtual packing volume ratio of a monodisperse fraction having a diameter equal to di

$$y_i=\frac{\Phi_i}{\sum_{i=1}^{n}\Phi_i},$$

where the partial volume Φ are the volume occupied by each class in unit bulk volume of the granular mix.

The value of packing volume ratio relates to the angularity number of aggregate. The higher is the angularity number of aggregate, the smaller is the value of packing volume ratio. The angularity number of aggregate depends on the parameters of aggregate which include flakiness ratio, roundness, convexity ratio, elongation ratio, shape factor and fullness ratio. The increase of elongation ratio leads to the increase of angularity number and the increase of flakiness ratio, roundness, convexity ratio, shape factor and fullness ratio leads to the decrease of angularity number (Mora and Kwan, 2000).

The highest is the packing volume ratio of aggregate, the strength of concrete is higher and the water absorption is lower.

Effects of addition of pozzolanic materials

The pozzolanic reaction primarily occurs between amorphous siliceous materials and calcium hydroxide to form calcium silicate hydrates.

At the basis of the pozzolanic reaction stands a simple acid-base reaction between calcium hydroxide, also known as Portlandite, or ($Ca(OH)_2$), and silicic acid (H_4SiO_4, or $Si(OH)_4$). For simplifying, this reaction can be represented as following:

$$Ca(OH)_2 + H_4SiO_4 \longrightarrow Ca^{2+} + H_2SiO_4^{2-} + 2\,H_2O \longrightarrow CaH_2SiO_4 \cdot 2\,H_2O$$

The main compounds formed from hydration of cement are hydrated calcium silicate and calcium hydroxide while calcium hydroxide is water-soluble and has no cementitious value. Calcium hydroxide may come out of the concrete with moisture, leaving voids in concrete. With the addition of pozzolanic materials, like pulverized fly ash (PFA), silica fume (SF) and metakaolin (MK), are chemically combined with calcium hydroxides and other soluble alkalis such as sodium hydroxides to produce calcium-silicate-hydrate (C-S-H). The CSH gel strengthens cement paste and filling the voids improving the impermeability of concrete.

With the use of pozzolanic materials in concrete, the early strength of concrete is reduced and later strength is increased. The pozzolanic materials are described as siliceous or siliceous and aluminous material which have little or no cementitious nature, but, in finely divided form and in the presence of moisture. It reacts with lime at ordinary temperatures to form compounds possessing cementitious properties.

Chan and Ji (1999) and Khatib (2008) determined that the compressive strength of concrete increases with the replacement of cement by PFA, MK and SF. They found that the optimum proportion of these pozzolanic materials replacing cement was about 15%

for concrete to reach its maximum 28 day strength. With this replacement proportion, the 28 day compressive strength of concrete increased by 14%, 10% and 19.5% with the replacement of PFA, MK and SF respectively.

It was also discovered that use of pozzolanic materials in concrete provided significant improvement of durability of concrete. The rate of chloride diffusion and sulfate degradation was reduced by more than 50% since the porosity of concrete was reduced due to the pozzolanic reaction induced to produce more C-S-H gel in concrete. (Courard et al., 2003; Batis et al., 2005)

2.3. Glass and Development of Recycling of Glass Waste

2.3.1. Introduction

Glass is a useful material that related to many parts of human life due to its hard and transparent properties. Glass waste represents a major part of solid waste among the world. In this section, the properties of glass are briefly introduced and the current situation of glass waste recycling is reviewed.

2.3.2. Properties of Glass

Glass is an amorphous (or non-crystalline) solid material. It is typically brittle, and often optically transparent. Glass is produced by initially heating silica (in the form of sand) to about 1600°C. As the mixture melts, silica-bonds break apart destroying the orderly structure of the solid crystal. The silicium-oxygen (Si-O) bonds of silica start to rebuild when it is cool down. It is an amorphous solid with ionic character and the bond energies are usually ranged from 210 kJ to 335 kJ. (Shi et al., 2007) The molecular structure of glass is presented in Figure 2.2.

Transparence glass without color, which is commonly used for windows and bottles, contains about 12% soda and 12% lime. Glass with red color is produced by adding small amounts of cadmium sulfide and selenide. Ordinary soda-lime glass is usually pale green due to iron impurities. Brown beer-bottle glass is colored with iron sulfides. Amber glass, which is commonly used for medicine bottles, is mixed with mixtures of sulfur and iron oxides.

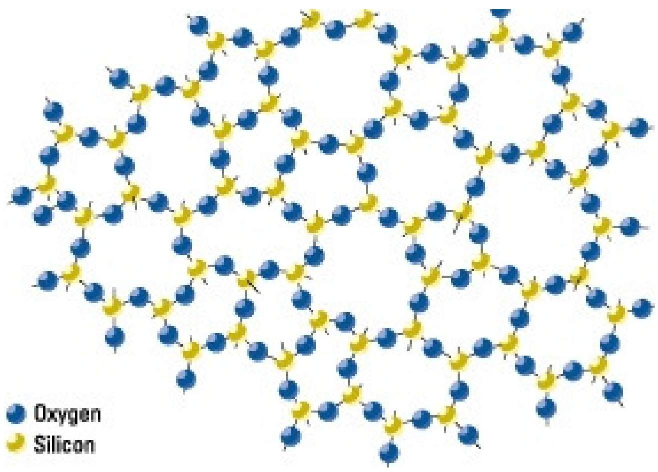


Figure 2.2 : Molecular structure of glass

Physical and mechanical properties of glass

Glass is strong and has excellent hardness due to its giant ionic structure. Its compressive strength, Young modulus and hardness (on Mohs Scale) are 50-60 MPa, 65-90 GPa and 5.5-6.5 respectively. It is strong but brittle because its molecular structure is composed of tetrahedral crystals which do not have a good large-area orderly crystalline structure and this structure gets ruptured when it is under stress. (Leadbettera and Wrigh, 1972)

Waste glass is generally crushed to particle form for recycling purposes. The shape of cullet is usually angular and sometimes elongated (see Figure 2.3). It is transparent and glazing so that a value added product can be possibly developed. Table 2.1 shows the physical properties of glass (Thomas and Terese, 2005).

Table 2.1 : Physical properties of different type of glass (Eric, 2007)

Properties	**Soda-lime glass (containers)**	**Glass wool (for thermal insulation)**	**Special optical glass (similar to Lead crystal)**	**Fused silica**
Transition temperature T_g (°C)	573	551	540	1140
Coefficient of thermal expansion (ppm/K)	9	10	7	0.55
Density (g/cm^3)	2.52	2.550	3.86	2.203
Refractive index n_D at 20°C	1.518	1.531	1.650	1.459
Dispersion at 20°C, $10^4 \times (n_F - n_C)$	86.7	89.5	169	67.8
Young's modulus (GPa)	72	75	67	72
Shear modulus (GPa)	29.8	--	26.8	31.3
Liquid temperature, °C	1040	--	--	1715
Heat capacity (J/(mol·K))	49	50	51	44
Surface tension (mJ/m^2)	315	290	--	--

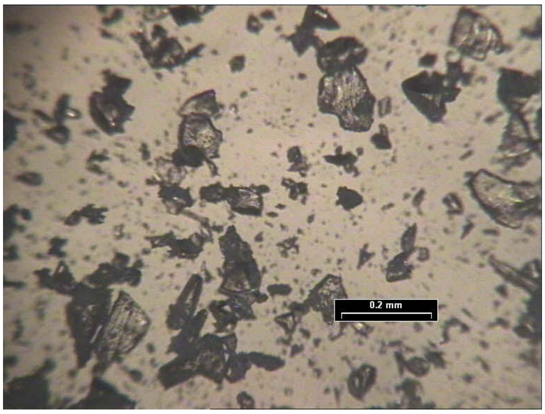


Figure 2.3 : Texture of crushed glass under microscope

Chemical properties of glass

The chemical compositions of glass are mainly SiO_2, and small proportions of Na_2CO_3, K_2CO_3 and CaO. These chemicals are abundant throughout the world.

The details of composition of each type of glass are shown in Table 2.2. Glass is in general, chemically inert, which is highly resistant to any form of chemical attack due to the strong covalent bonding of Si-O structure. Only a few aggressive chemicals have the ability to attack glass including acid, hot concentrated alkali solutions and water with very high temperature.

Table 2.2 : Chemical compositions of different glass type (Eric, 2007)

	Typical Soda-lime (container) glass (%)	Typical float glass (%)	Typical TV panel glass (%)	Typical low expansion borosilicate glass (%)	LCD glass (%)
SiO_2	74.42	71.86	71.93	83.34	60.04
Al_2O_3	0.75	0.08	1.42	1.33	1.62
MgO	0.30	5.64	--	--	0.0169
CaO	11.27	9.23	0.06	--	0.261
SrO	--	--	6.23	--	--
BaO	--	--	4.23	--	--
Li_2O	0.00	--	0.02	--	--
Na_2O	12.9	13.13	8.66	4.08	0.0614
K_2O	0.19	0.02	5.63	0.04	0.132
Fe_2O_3	0.01	0.04	0.02	--	0.91
TiO_2	0.01	0.01	0.38	--	--
Sb_2O_3	--	--	0.07	--	--
ZnO	--	--	0.44	--	--
ZrO_2	--	--	0.79	--	--

Alkali attacks glass surface and the surface simply dissolves. This process continuously exposes fresh surface which in turn is dissolved and corrode uniformly if sufficient amount of alkali is present in the glass. Acid corrodes glass by dissolving the alkali in composition of glass, a porous surface is left that consists of the silica network with holes where the alkali has been removed by the acid. The rate of attack is then reduced due to the pore formed as the acid must penetrate this surface layer to find alkali to dissolve. For the mechanism of water corrosion, it is similar to acid corrosion that alkali is removed from glass surface. Water corrosion acts at a much slower rate unless it is at a very high temperature (over 250^{o}C).

2.3.3. Recycling of glass among the world

Recycling of waste glass is not just good for the environment and saving the space of landfill, it also reduces the production cost of glass products. For every additional 10% of recycled glass that is used in the making of new bottles, it saves 2.5% in energy costs to make the new glass as opposed to just using raw materials (sand, soda ash and limestone). (Sacramento, 2009)

However, it is difficult to produce new products with high quality. When factory mix all glass, plastic and recyclables together, there is a chance the glass will be contaminated and unusable for recycling. Most local-level recycling facilities do not have the technology to properly sort all materials, which allow plastic and other wastes to get into the glass recycling stream.

In Hong Kong, government data (see Table 2.3) (EPD, 2007) has shown that about 300 tonnes of glass waste is generated everyday, however, the recovery rate is only about 1-2%. This situation may be due to the fact that no local glass manufacturing industry is in Hong Kong to serve as a viable recycling outlet.

But recently, Hong Kong Government launched a programme called "Glass Container Recycling Programme". This programme is to encourage different sector, especially hotels, to separate the waste glass containers from other waste and dispose separately. The recycling contractor will then collect these waste regularly and crush the waste glass containers to produce engineering materials to replace river sand for the production of paving blocks. (EPD, 2008)

Table 2.3 - Quantities of waste glass recovered and disposed of in HK (2006)

	Recovered (tonnes)	Disposal (tonnes)
Soda-lime (container) Bottles	3,000	83,000
Other Glass	0	29,000
Total	3,000	112,000

In the United States, there was approximately 13.2 million tonnes of post-consumer glass discharged in the municipal waste stream in 2006 which made up 5.2% of total municipal solid wastes generated. About only 22% of glass waste were recovered which was about 18% higher than the recovery rate of Hong Kong. (EPA, 2006)

In UK, there are around 3.4 million tones of glass entering the UK waste stream annually which make up 7% of the household waste generated. The government setup over 50,000 'bottle banks' at different districts of UK for the collection of waste glass bottles to raise the public concern on waste recycling. The recycling rate of waste glass bottles had a significant increase since 1998 and the percentage of recycling was raised to 36% in 2003 (See Figure 2.4). (British Glass, 2006; WRAP, 2005)

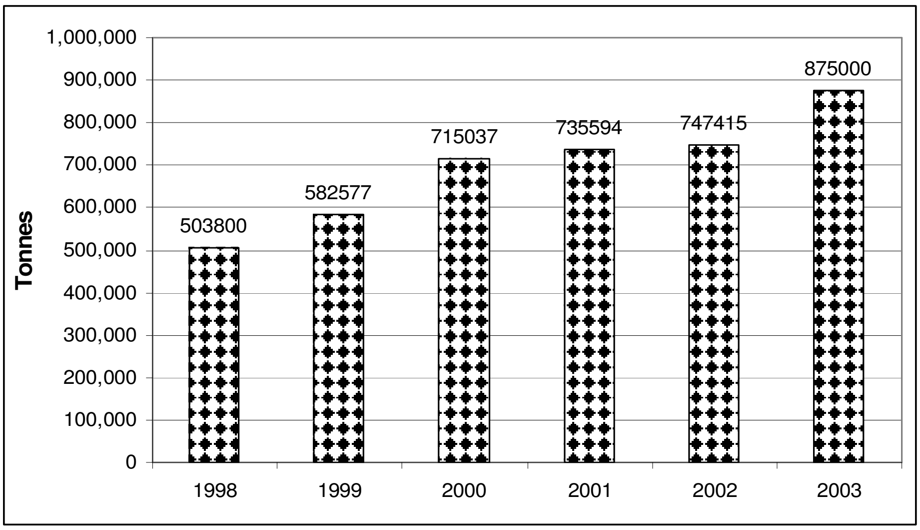


Figure 2.4 : Trends in UK container glass recycling, 1998-2003

Figure 2.5 shows the recycling rate of waste glass among European countries in 2008. In Germany, Finland, Switzerland and the Netherlands, the recycling rates of glass container waste were more than 80% (Poutos et al, 2008). It is obvious that European countries have the highest recycling rate of waste glass comparing with others.

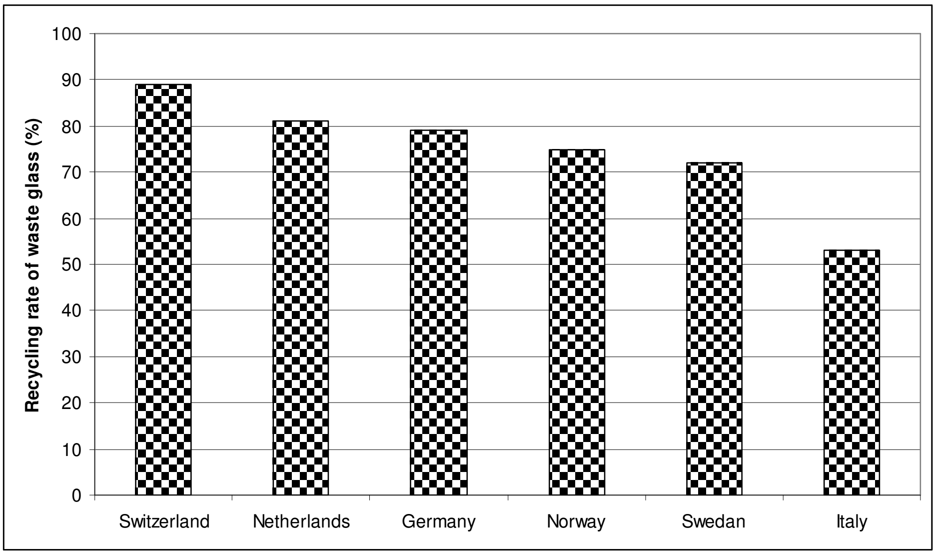


Figure 2.5 : Recycling rate of waste glass at European countries at 2008 (Poutos et al., 2008)

2.4. Use of Waste Glass in Concrete

2.4.1. Introduction

There are several advantages of using crushed glass cullet as aggregates in concrete. Firstly, glass has nearly zero water absorption which makes it a very durable material. Secondly, its excellent hardness gives the concrete strong abrasion resistance comparing with using natural crushed granite. Moreover, very fine glass has pozzolanic properties which can serve both as a partial cement replacement and as a filler (Meyer, 2003). Laboratory tests have indicated that the properties of concrete using glass as aggregates depend on the particle size and percentage of glass in the concrete mixtures (Topcu and Canbaz, 2004; Park et al., 2004; Ismail and Haswhmi, 2009; Sangha et al., 2004; Limbachiva, 2009).

Besides, reuse of waste glass in concrete mixture reduces the amount of solid waste which preserves landfill space and saves waste disposal costs.

In this section, findings of researches on the effects of using recycled glass in concrete of its fresh and hardened properties, are reviewed.

2.4.2. Fresh Properties of Concrete Containing Recycled Glass

Slump

Park et al. (2004) conducted an experiment on using crushed glass (fineness modulus ~ 3.48) to replace sand by 30%, 50% and 70%. The slump of fresh concrete is reduced by 23%, 33% and 42% respectively comparing with control mix (0% replacement). He explained that the reduction of slump with the increase of glass content is due to the following reasons: 1) with the increase of glass content, the cement paste attached to the surface of the waste glass was increased which resulted in less available cement paste for the fluidity of the concrete mixture; 2) waste glass was sharper, larger and more angular than sand which results in less fluidity.

Air content

The air content of concrete increased with the increase of glass content because of the irregularly angled grain shape of the waste glass cullet to trap the air. Therefore, the air content increased with the increase of glass content. (Park et al., 2004) He reported that the air content of concrete mixtures increased with the increase of waste glass content in concrete. With waste glass (fineness modulus = 3.47) replace sand by 30%, 50% and 70%, the air content of concrete was increased by 16.9%, 27.1% and 36.0% respectively.

2.4.3. Hardened Properties of Concrete Containing Recycled Glass

Hardened density

The hardened density of concrete is reduced if sand is partially replaced by glass cullet as density of glass (about 2,450 kg/m^3) is smaller than sand (~2,600 kg/m^3). The hardened density reduced by about 3% when waste glass cullet is used to replace sand (by 20% by weight) provided that the water-cement ratio, the aggregate-cement ratio remained unchanged. (Batayneh et al., 2007)

Compressive strength, tensile strength and modulus of elasticity

The compressive strength and modulus of elasticity of concrete decrease with the increase of glass content in concrete. This is due to the decrease in adhesive/bond strength between the surface of the waste glass cullet and the cement paste. (Ismail and AL-Hashmi, 2009; Metwally, 2007; Poon and Chan, 2007) Modulus of elasticity was also reduced with the reduction of compressive strength.

However, the strength of concrete increased if very fine glass particle was used owing to its pozzolanic property. Shao et al. (2000) prepared concrete with waste glass cullet with three different particle sizes including <150μm, <75μm and <38μm to replace sand in concrete (by 30% by weight) while keeping the water-cement ratio and aggregate-cement ratio constant. The measured 28-day compressive strength of the zero replacement (control), <150μm, <75μm and <38μm glass cullet were 23.5, 19.5, 21 and 25.3 MPa respectively. The compressive strength of the concrete with <38μm glass cullet was 7.66% higher than that of the control.

The compressive strength of concrete is very sensitive of the particle size of glass used in concrete which is directly related to the ASR and pozzolanic effects. This aspect will be discussed in section 2.5.

2.5. ASR Expansion and Pozzolanic Properties of Concrete Incorporate with Recycled Glass

2.5.1. Introduction

It has been known that use of waste glass cullet as aggregate may cause serious expansion and cracking of concrete due to the alkali-silica reaction (ASR). The level of expansion deterioration depends on two main factors, size and color of waste glass cullet being used. However, glass itself is not just bringing adverse effect to concrete. It also has pozzolanic property if its particle size is small enough which may be beneficial to the durability and strength of concrete.

In this section, the effect of color and particle size of glass on ASR, the effect of size of glass on pozzolanic reaction are reviewed and discussed.

2.5.2. Effect of Color of Recycled Waste Glass in Concrete

Yamada et al. (2004) conducted experiments to study how the color and size of the glass affected the ASR expansion of concrete. Three colors of glasses used including green, brown and clear (white). It was found that green color glass caused minimum expansion and clear color causes maximum expansion. Chromium oxide (Cr_2O_3) gives rise to the green color in glass which also acts as a suppressor to help reducing of ASR expansion. White glass contains more active silica so that the concrete produced suffer most from ASR (Topcu et al., 2008).

2.5.3. ASR Expansion of Glass with Different Particle Size in Concrete - Elaborate with Fracture Mechanics

Yamada et al. (2004) and Bazant et al. (1998) used of a fracture mechanic approach to explain the relationship between ASR expansion of concrete and glass particle size.

They suggested that the ASR expansion of concrete is directly proportional to the volume of glass that has undergone ASR (V_a) and inversely proportional to the square root of diameter of the glass particle (D) which can be expressed using the following equation:

$$\varepsilon_i = A_2 V_a - \frac{A_1}{\sqrt{D}}$$

Where ε_i is the expansion length of concrete, A_1, A_2 are constants.

Experiment conforming to ASTM C1260 was conducted and proofed that the theory is true. When the glass particle size is between 300-600μm, the expansion of concrete is the largest. This range of size of glass particles is called 'pessimum size'. (see Figure 2.6) This pessimum size can shift depends on the properties of glass particles. (Yamada et al., 2004)

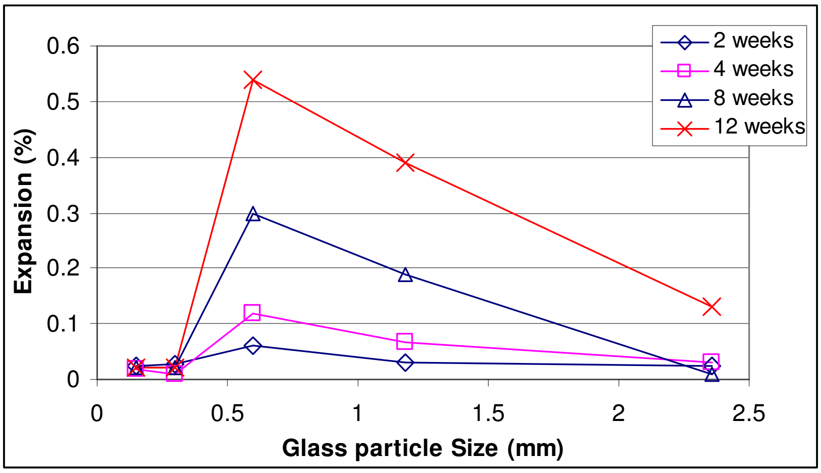


Figure 2.6 : ASR Expansion growth of specimen (Yamada et al. ,2004)

Bazant et al. (1998) also suggested that the tensile strength (f'_t) and compressive strength (f'_c) of concrete with glass particles could be expressed using the following equation

$$f'_t = f'_0 + \frac{C_1}{\sqrt{D}} - C_2 \frac{V_a}{V_g} \text{ and}$$

$$f'_c = \left(\frac{f'_t}{6}\right)^2 \text{ in psi unit,}$$

where f'_0 is residual strength which is size insensitive, C_1 and C_2 are constant, V_g is the total volume of glass.

They found that the strength of concrete is independent of the diameter of glass while the glass particles are small enough, and independent of volume of reacted glass while glass particles are large enough.

With the reduction of glass particle size from 10mm to 2.36mm and 1.18mm in concrete, the compressive strength decreased by 20% and 26% due to the increase of surface area leading to the increase of seriousness of ASR deterioration. For further decrease of glass particle size to from 1.18mm to 0.6mm and 0.15mm, the strength of concrete increased by 10% and 37% respectively since all the glass had reacted.

2.5.4. Pozzolanic reactivity of waste glass with different particle sizes

Glass is classified as a pozzolanic material as if contains high silica content and its pozzolanic reactivity depends on its chemical composition and particle size of glass cullet.

Shi et al. (2005) tested the pozzolanic activity of fly ash and glass cullet of four different sizes which included 700-40μm, <700μm (with 20% particles smaller than 10μm), <100μm and <50μm.The results indicated that the pozzolanic activity of fly ash and glass 700-40μm, <700μm, <100μm and <50μm were 83%, 68%, 93%, 111% and 117% respectively at the age of 28 day. The glass with particle size <100μm and <50μm had pozzolanic activities even higher than fly ash by 20% and 38% respectively.

Wang (2008) studied the effect of LCD glass sand on the properties of concrete. The SEM image indicated that dense C-S-H gel was produced in the glass sand concrete. (see Figure 2.7) The microstructure of concrete was denser comparing with the one without any replacement. He also discovered that the durability of concrete, which included chloride ion diffusion resistance, sulfate attack resistance, water absorption and electrical resistance were significantly improved.

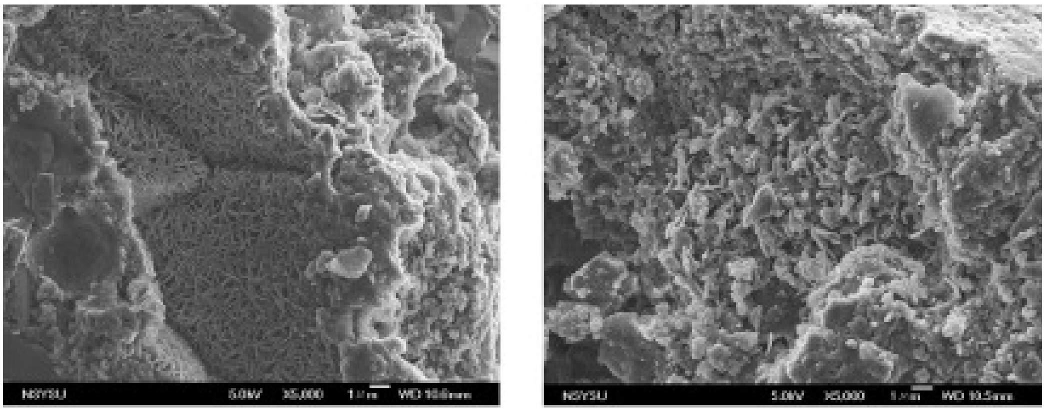


Figure 2.7 : SEM image of concrete without (left) and with LCD glass (right) (Wang, 2008)

Turgut and Yahlizade (2009) investigated the use of various levels (10%, 20% and 30%) of fine glass (<4.75mm) and coarse glass (4.75-12.5mm) as replacements of aggregate to produce concrete blocks. They concluded that the maximum compressive strength was obtained when 20% of fine glass was used. However, increasing the content up to 30% slightly reduced the strength. On the other hand, increasing the coarse glass content from 10% to 30% led to a gradual increase in compressive strength of the paving blocks. Turgut (2008) showed that moulded masonry blocks made with waste glass powder had higher compressive strength than that made with waste limestone dust. Decreasing the water-cement ratio from 0.5 to 0.3 of the concrete block seemed to result in an increase in the compressive strength.

Lam et al. (2008) studied the influence of recycled crushed glass (RCG) on the properties of dry-mixed concrete paving block prepared by using an aggregate/cement ratio of 4. The RCG (fineness modulus of 4.25) was used to replace recycled aggregate (fineness modulus of 3.54) at the replacement levels of 25%, 50% and 75%. They found that the

28-day compressive strength of the paving blocks were 56 MPa, 54 MPa and 57 MPa, respectively. Furthermore, they found that the use of coarser particle size RCG led to better packing of the paving blocks produced which would result in higher density of the hardened concrete blocks.

Corinaldesi et al. (2005) conducted a study using very small size of crushed glass with different grading including 36µm, 36-50µm and 50-100µm to replace natural fine aggregates (by 30% and 70% by weight) in mortars. It was found that the mechanical strength of mortar increased with the replacement of glass. The smaller the size of glass granules, the higher was the mechanical strength of the mortar. It was due to the reaction between cement and glass particles which led to a dense microstructure of concrete as observed by SEM. It was also determined that the percentage of porosity in the mortars increased with the increase of size of crushed glass used.

Girbes et al (2004) conducted an experiment using waste glass to partially replace portlant cement. It was found that the strength of cement mortar increased. The size of the glass was one of the determination factors affecting the strength of the cement paste. The smaller the size of glass particles, the higher is the strength of cement mortar.

Shao et al. (2000) used three different size of waste glass including 38µm, 38-75µm and 75-150µm to replace 30% cement by volume in concrete. It was found that the finer the glass power, the higher was the pozzolanic activity which led to the higher mechanical strength of concrete. The strength of concrete was higher than control which had zero replacement while the size of glass waste was smaller than 38µm. That explained why the strength of concrete was enhanced when very fine glass particles was present in the concrete mixture.

2.6. Summary

1. In the construction industry, the wet-mixing method is implied on the production of structural concrete and dry-mixing method is used for the production of pre-casted concrete blocks. For wet-mixed concrete, high flowability of concrete mixture is produced during concrete casting which is able to produce different shape of structrual concrete and bonds well to the steel reinforcement. The concrete mixture of dry-mixed concrete is prepared with only sufficient cohesion but zero workability that enable demoulding after fabrication which is effective for mass production.
2. The behaviour of concrete depends on the physical properties of aggregates such as sharp, texture and strength influence the strength of concrete; and the chemical properties of aggregates such as alkali content and pozzolanic material content would beneficially and adversely influence the strength and durability of concrete.
3. The increase of packing volume ratio of aggregates leads to the increase of compressive strength and reduce of water absorption of concrete and the value of packing volume ratio depends on the flakiness, sphericity, shape and elongation ratio of aggregates. The grading and size distribution of aggregate are directly influence the strength of concrete.
4. Glass is hard, transparent and chemically stable in nature which makes it an useful material. However, the disposal and recycling of the glass waste is also a critical

issue. In Hong Kong, the recycling rate of waste glass is very low comparing with other European country due to the high operation cost and low profit. Therefore, there is a need to develop new ways to recycle waste glass.

5. The use of recycled waste glass to replace sand in concrete influences in the properties of concrete in several aspects. It leads to the reduction of workability, and increase of air content of concrete due to the large angularity of glass which results in lower flowability and poor packing of aggregates. The chemical properties of aggregates (alkali content and pozzolanic material content) influence the strength and durability of the concrete. The strength of concrete decreases because the bond strength decreases between the smooth surface of glass and cement paste, except that the particle size of glass is fine enough (usually less than 150μm).
6. The use of recycled waste glass in concrete leads to the increase of ASR expansion. However, the ASR expansion decreases with the reduction of particle size of glass due to the increase of pozzolanic reaction of reactive silica presented in glass.
7. The ASR expansion and strength of concrete vary with the variation of particle sizes of glass particle used in concrete. If the size is large enough, with the reduction of size of glass, the strength decreases and ASR expansion is increased.
8. The pozzolanic reaction increases with the reduction of size of glass particle used in concrete. It is because the amount of reactive silica increases with the increase of surface area of the glass particle.

Chapter 3 – Methodology

3.1. Introduction

In this chapter, materials for concrete samples, details of sample preparation, mixing procedures and testing procedures are illustrated.

3.2. Materials

3.2.1. Cementitious materials

Ordinary Portland cement (OPC) complying with BS 12 and ASTM Type I was used as the cementitious material. Fly ash (PFA) and metakaolin (MK) were used as pozzolanic materials. The chemical compositions and physical properties of all these cementitious materials are presented in Table 3.1.

Table 3.1: Chemical composition and physical properties of cementitious materials

	Cement	PFA	MK
SiO_2 (%)	19.61	56.79	53.20
Fe_2O_3 (%)	3.32	5.31	0.38
Al_2O_3 (%)	7.33	28.21	43.90
CaO (%)	63.15	<3	0.02
MgO (%)	2.54	5.21	0.05
SO_3 (%)	2.13	0.68	-
Na_2O (%)	-	-	0.17
K_2O (%)	-	-	0.10
TiO_2 (%)	-	-	1.68
Loss on Ignition (%)	2.97	3.9	0.50
Density (kg/m^3)	3,160	2,310	2,620
Specific Surface Area (cm^2/g)	3,520	3,960	12,680

3.2.2. Natural Fine Sand

Natural fine river sand was used as the fine aggregate. It has maximum particle size of 2.36 mm, density and fineness modulus are 2,630 kg/m^3 and 2.46 respectively.

3.2.3. Natural Coarse Aggregate

Crushed natural granite, with a nominal size of 10 mm and a fineness modulus of 6.01, was used as the coarse aggregate.

3.2.4. Recycled Fine Glass (FG)

The recycled fine glass (FG) was post-consumer green bottles obtained locally from a waste glass recycler. The recycled glass bottles were crushed and sieved into particle sizes. The particle size of the crushed glass was sorted into four classes (A-FG, B-FG, C-FG and D-FG) according to their particle sizes (A-FG - un-sieved, B-FG <2.36 mm, C-FG <1.18mm and D-FG <0.6mm) respectively.

The physical properties of the coarse and fine aggregate are presented in Table 3.2 and their gradation curves are shown in Figure. 3.1.

Table 3.2: Physical properties of coarse and fine aggregates

	Coarse aggregate	Fine aggregate				
		Sand	A-FG un-sieved	B-FG <2.36mm	C-FG <1.18mm	D-FG <600µm
Density (kg/m^3)	2,650	2,630	2,470	2,470	2,470	2,470
Fineness modulus	6.01	2.46	3.29	3.03	2.33	0.43
Water absorption (%)	1.45	1.2	0.30	0.31	0.35	0.48
Shape	Angular	Rounded	Very angular & flattened		Angular	Angular
Surface texture	Rough	smooth	Smooth and impermeable			

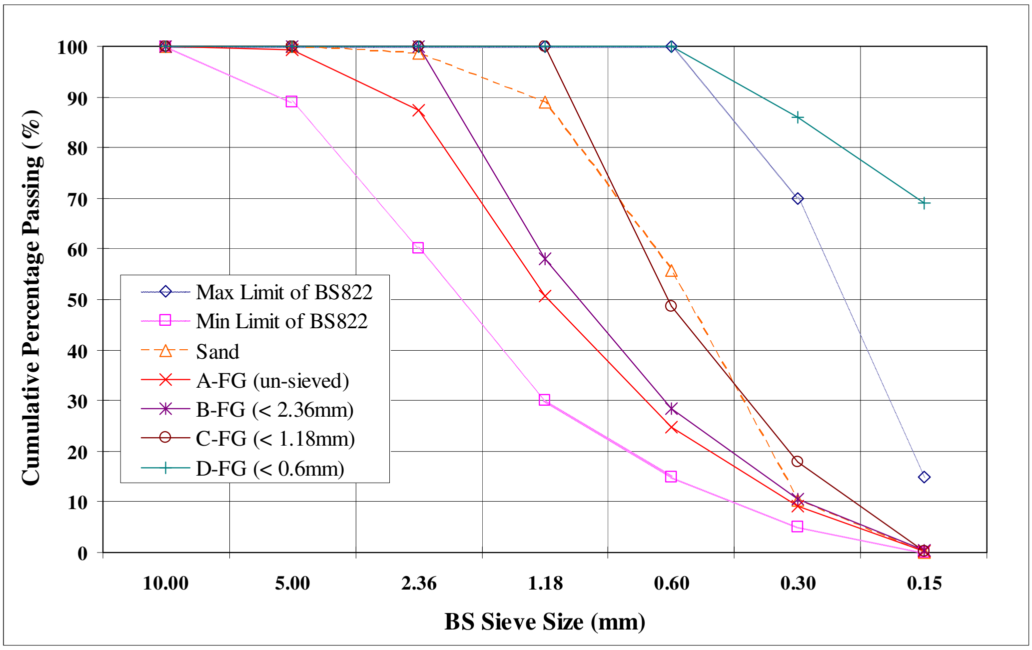


Figure 3.1: Grading curves of fine aggregates

The most important difference between the natural sand and the recycled fine glass (FG) aggregate was its physical shape and texture. The shapes of FG were generally angular and contained some elongated and flat particles, while the texture was smooth. The shape of the natural sand used could be considered as more rounded and rougher than that of FG. Figure 3.2 shows the shape of sand and FG observed under an electronic microscope for comparison and Figure 3.3 shows the four class of FG.

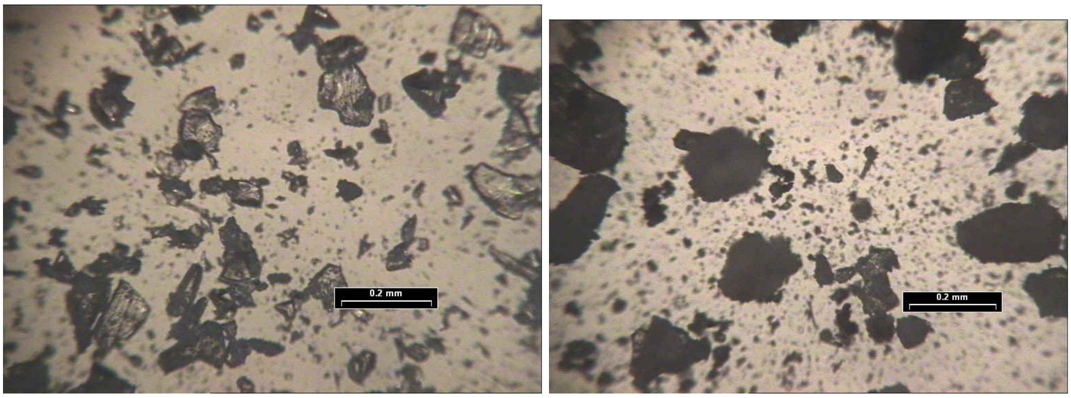


Figure 3.2: The shape and surface texture of (a) D-FG and (b) sand

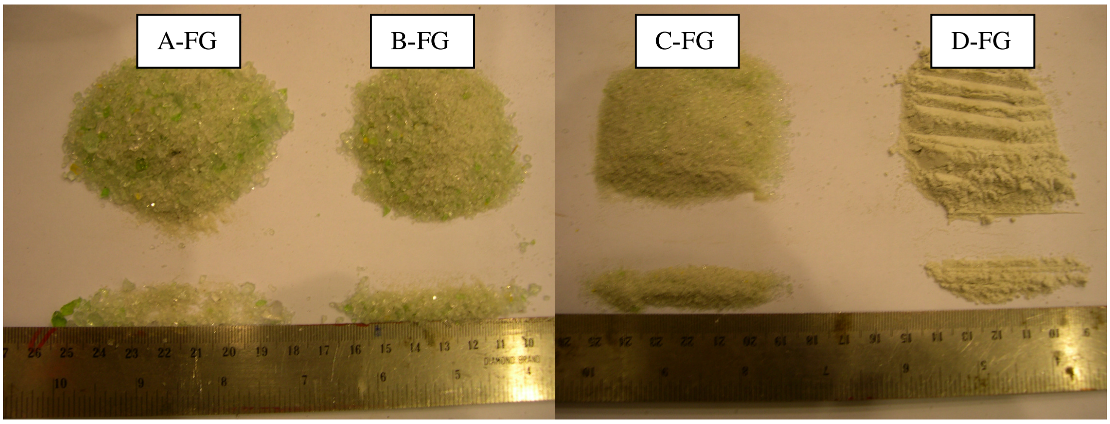


Figure 3.3: Recycled find glass, A–FG(un-sieved), B-FG(<2.36 mm), C-FG(<1.18mm) and D-FG (<600µm)

3.2.5. Superplasticizer

A sulfonated naphthalene formaldehyde condensate (Darex Super 20) with a density of 1210 kg/m^3 in liquid form was used in the concrete mixes. It was used to control the workability of the wet-mixed concrete blocks and mortar bars.

3.3. Mix proportions

In this research, dry-mixed and wet-mixed concrete blocks and mortar bars were prepared to determine the effect of different particle size of recycled fine glass (FG) on the porperties and ASR resistance. The mix proportions are illustrated below.

3.3.1. Dry-mixed and wet-mixed concrete blocks

For dry-mixed and wet-mixed concrete blocks, the mix ratio by weight for the control was cement: coarse aggregate: fine aggregate = 1: 2: 2. In addition to the control mix, four additional series of concrete block mixes were prepared using crushed glass with four different particle size distributions A-FG, B-FG, C-FG and D-FG. In each of the series, four concrete blocks were prepared by replacing sand with glass at the levels of 25%, 50%, 75% and 100%.

The dry-mixed concrete blocks were prepared with only sufficient water to produce sufficient cohesion of materials but with no slump/workability.

For the wet-mixed concrete blocks, the water-cement ratio was 0.45 and varying amounts of superplasticizer added into the mixes to maintain a constant workability.

The mixing proportions of the dry-mixed and wet-mixed concrete blocks are presented in Table 3.3 and Table 3.4 respectively.

Table 3.3: Mix proportions of dry-mixed concrete blocks (by weight)

Mix notation	Cement	Coarse aggregate	Fine aggregate					W/C
			Sand	A-FG	B-FG	C-FG	D-FG	
DM-Control	1.0	2.0	2.0	-	-	-	-	0.270
DM-A-25	1.0	2.0	1.5	0.5	-	-	-	0.264
DM-A-50	1.0	2.0	1.0	1.0	-	-	-	0.257
DM-A-75	1.0	2.0	0.5	1.5	-	-	-	0.251
DM-A-100	1.0	2.0	-	2.0	-	-	-	0.244
DM-B-25	1.0	2.0	1.5	-	0.5	-	-	0.265
DM-B-50	1.0	2.0	1.0	-	1.0	-	-	0.260
DM-B-75	1.0	2.0	0.5	-	1.5	-	-	0.254
DM-B-100	1.0	2.0	-	-	2.0	-	-	0.249
DM-C-25	1.0	2.0	1.5	-	-	0.5	-	0.270
DM-C-50	1.0	2.0	1.0	-	-	1.0	-	0.270
DM-C-75	1.0	2.0	0.5	-	-	1.5	-	0.270
DM-C-100	1.0	2.0	-	-	-	2.0	-	0.270
DM-D-25	1.0	2.0	1.5	-	-	-	0.5	0.281
DM-D-50	1.0	2.0	1.0	-	-	-	1.0	0.293
DM-D-75	1.0	2.0	0.5	-	-	-	1.5	0.305
DM-D-100	1.0	2.0	-	-	-	-	2.0	0.317

Table 3.4: Mix proportions of wet-mixed concrete blocks (by weight)

Mix notation	Cement	Coarse aggregate	Fine aggregate					W/C
			Sand	A-FG	B-FG	C-FG	D-FG	
*WM-Control	1.0	2.0	2.0	-	-	-	-	0.450
WM-A-25	1.0	2.0	1.5	0.5	-	-	-	0.450
WM-A-50	1.0	2.0	1.0	1.0	-	-	-	0.450
WM-A-75	1.0	2.0	0.5	1.5	-	-	-	0.450
WM-A-100	1.0	2.0	-	2.0	-	-	-	0.450
WM-B-25	1.0	2.0	1.5	-	0.5	-	-	0.450
WM-B-50	1.0	2.0	1.0	-	1.0	-	-	0.450
WM-B-75	1.0	2.0	0.5	-	1.5	-	-	0.450
WM-B-100	1.0	2.0	-	-	2.0	-	-	0.450
WM-C-25	1.0	2.0	1.5	-	-	0.5	-	0.450
WM-C-50	1.0	2.0	1.0	-	-	1.0	-	0.450
WM-C-75	1.0	2.0	0.5	-	-	1.5	-	0.450
WM-C-100	1.0	2.0	-	-	-	2.0	-	0.450
WM-D-25	1.0	2.0	1.5	-	-	-	0.5	0.450
WM-D-50	1.0	2.0	1.0	-	-	-	1.0	0.450
WM-D-75	1.0	2.0	0.5	-	-	-	1.5	0.450
WM-D-100	1.0	2.0	-	-	-	-	2.0	0.450

*Certain amount of superplasticizer is added to mixes to maintain the same workability

3.3.2. Dry-mixed and wet-mixed mortar bar

Mortar bars (25×25×285 mm) with a fixed cement to fine aggregate ratio of 1:2.25 were prepared. Four different particles size of recycled fine glass (A-FG, B-FG, C-FG and D-FG) were used as a full replacement (100%) of river sand by mass in all mixes.

For each mix proportion, the mixing ratio mentioned above were kept constant except for the water content in the production of wet-mixed and dry-mixed mortar bars. For wet-mixed method, the water to cement ratio was kept constant at 0.45 and varying amounts of superplasticizer was used to maintain the workability constant for all mixes. The mix proportions of the wet-mixed and dry-mixed mortar bars for five different fine types of aggregates including sand (control) constituents are presented in Table 3.5.

Table 3.5: Mix proportions of wet-mixed and dry-mixed mortar bars (by weight)

Mix Notation	Cement	Sand	FG-A	FG-B	FG-C	FG-D	W/C
WM-Control	1.00	2.25	-	-	-	-	0.45
WM-A	1.00	-	2.25	-	-	-	0.45
WM-B	1.00	-	-	2.25	-	-	0.45
WM-C	1.00	-	-	-	2.25	-	0.45
WM-D	1.00	-	-	-	-	2.25	0.45
DM-Control	1.00	2.25	-	-	-	-	0.27
DM-A	1.00	-	2.25	-	-	-	0.27
DM-B	1.00	-	-	2.25	-	-	0.28
DM-C	1.00	-	-	-	2.25	-	0.29
DM-D	1.00	-	-	-	-	2.25	0.34

3.3.3. Dry-mixed and wet-mixed mortar bar prepared with addition of PFA and MK

The dry-mixed mortar bar specimens with the inclusion of PFA and MK were also prepared in order to further investigate the effect of different admixture contents on the ASR expansion. The specimens were prepared with four different particles size with 100% recycled glass. For each particular size of glass, PFA and MK at dosages of 5, 10 and 20% by weight of cement were added in the mortar mixtures. The mix proportions of dry-mixed mortar bar prepared with PFA and MK are shown in Tables 3.6 and 3.7 respectively.

Table 3.6: Mix proportions of dry-mixed mortar bar prepared with PFA (by weight)

Mix Notation	Cement	FG-A	FG-B	FG-C	FG-D	PFA (%)
DM-A-P5	1.00	2.25	-	-	-	5
DM-A-P10	1.00	2.25	-	-	-	10
DM-A-P20	1.00	2.25	-	-	-	20
DM-B-P5	1.00	-	2.25	-	-	5
DM-B-P10	1.00	-	2.25	-	-	10
DM-B-P20	1.00	-	2.25	-	-	20
DM-C-P5	1.00	-	-	2.25	-	5
DM-C-P10	1.00	-	-	2.25	-	10
DM-C-P20	1.00	-	-	2.25	-	20
DM-D-P5	1.00	-	-	-	2.25	5
DM-D-P10	1.00	-	-	-	2.25	10
DM-D-P20	1.00	-	-	-	2.25	20

Table 3.7: Mix proportions of dry-mixed mortar bar prepared with MK (by weight)

Mix Notation	Cement	FG-A	FG-B	FG-C	FG-D	MK (%)
DM-A-M5	1.00	2.25	-	-	-	5
DM-A-M10	1.00	2.25	-	-	-	10
DM-A-M20	1.00	2.25	-	-	-	20
DM-B-M5	1.00	-	2.25	-	-	5
DM-B-M10	1.00	-	2.25	-	-	10
DM-B-M20	1.00	-	2.25	-	-	20
DM-C-M5	1.00	-	-	2.25	-	5
DM-C-M10	1.00	-	-	2.25	-	10
DM-C-M20	1.00	-	-	2.25	-	20
DM-D-M5	1.00	-	-	-	2.25	5
DM-D-M10	1.00	-	-	-	2.25	10
DM-D-M20	1.00	-	-	-	2.25	20

3.4. Preparation of specimens

3.4.1. Preparation of dry-mixed concrete blocks

Blocks were fabricated in steel moulds with internal dimensions of 70x70x70 mm using a dry-mix method which simulated the actual industrial production process of concrete blocks. After mixing the materials in a pan mixer, about 0.9 kg of the materials were placed into the mould in three layers. The first two layers were compacted manually by hammering a wooden plank on the surface layer to provide an evenly distributed compaction. The last layer was prepared by slightly overfilling the top of the mould (approximately 5mm) and the overfilled materials were subjected to a static compaction twice by using a compression machine. The load was increased at a rate of 600kN/min until 500kN was reached for the first compaction. After removing the excessive materials with a trowel, a second compaction was applied at the same rate until 600 kN was reached. The concrete blocks were demoulded after 24 hours.

The blocks were divided into two groups. The first group was stored in a water tank at an average temperature of 25±3 °C, and the second group of specimens was left in the laboratory environment at an average temperature of 23±3 °C and 75 relative humidity until the date of testing.

3.4.2. Preparation of wet-mixed concrete blocks

The mixed materials were first placed in concrete mixer and mixed for about 1 minute. Water and superplasticizer (Darex Super 20) were mixed together and then added into the mixer to mix for about 2 minutes. The slump of the concrete mixtures were controlled at a high level within 150~160mm in order to provide good compaction during vibration compaction. After concrete casting and vibration compaction for about 1 minute, the prepared samples were kept in a laboratory environment (T= 23^{o}C RH=75%) and covered with an impermeable plastic sheet to prevent evaporation of water.

All of the samples were demoulded one day after casting. Six samples were air-cured in an environmental chamber with a constant temperature of 20^{o}C and 50% humidity (air-cured) and the other six were wet-cured in a water bath with a constant temperature of 25^{o}C.

3.4.3. Preparation of wet-mixed and dry-mixed mortar bar

Cement and fine aggregate materials were first placed in a pan mixer and mixed for about 1 minute before water was added. Superplasticizer thoroughly pre-mixed with water was added to the mixer, and the mixing was continued for another 2 minutes.

The freshly wet-mixed materials were placed into the mortar bar mould in two layers of approximately equal depth. After each layer was filled, a uniform vibration was applied on a vibrating table.

For the dry-mixed method, the mixes were prepared with only sufficient water to produce a cohesive mix but with zero slump. After mixing the materials in the pan mixer, the materials was placed into the mortar bar mould in four layers of about equal thickness. Compression force was applied manually by hammering a wood stem on the surface layer to provide an evenly distributed compaction for the first three layers. At the fourth layer, the overfilled materials were subjected to a static compaction force by using a compression machine. The force was increased at the rate of 600 kN/min for 50 seconds for the first static compaction. The excessive materials were then removed to provide a good surface texture and second compaction was applied at the same rate until it reached 500 kN. (See Figure 3.4) After casting, all the wet-mixed and dry-mixed mortar bar specimens were covered with a plastic sheet in the laboratory at 23±3°C and 75 relative humidity. After one day, all the specimens were demoulded and stored in a water tank at an average temperature of 25±3 °C until the day of testing.

Figure 3.4: Fabrication of dry-mixed mortar bars

3.5. Test methods

3.5.1. Fineness modulus of fine aggregates

To characterize the overall coarseness or fineness of fine aggregate in this study, the fineness moduli (FM) of the fine aggregates were determined according to BS 812.

3.5.2. Theoretical packing volume ratio

The concept of aggregate packing was first noticed since Fuller and Thompson (1907) proposed the ideal grading curve. Less voids between aggregate particles, obtained as the grading curve of the aggregate particles, were close to the ideal grading curve.

With the evolvement of advanced computer technology in recent decades, various numerical models such as the Compressive Packing Model (CPM) have been developed to estimate the packing volume ratio of aggregates (Larrard and Thierry, 2002; Larrard, 1999). The CPM is based on the concept of virtual packing volume ratio and compaction index. The virtual packing volume ratio is defined as the maximum packing volume ratio achievable within a given mixture, each particle keeping its original shape and being placed one by one. The virtual packing volume ratio is also affected by the loosening and wall effects.

A computer programme model based on CPM theory proposed by Larrard F. de (1999) was developed by Lam (2006) and used to determine the theoretical packing volume ratio of the aggregates used for the block production.

3.5.3. Hardened density

The hardened density of specimens was determined using a water displacement method according to BS 1881.

3.5.4. Water absorption

Water absorption of the concrete block specimens was determined according to AS/NZS 4456.14.

3.5.5. Compressive strength

The compressive strength of the concrete block specimens was measured according to BS 6717. A Denison compression machine with a maximum capacity of 3,000 kN was used to determine the strength. A pair of 3 mm thick plywood was placed at the top and bottom of each concrete block specimens to ensure an even surface before the load was applied. The compression load was applied at the rate of 400 kN per minute until the specimens failed. The compressive strength of specimen was calculated by dividing the maximum load obtained by the load area of the specimen.

3.5.6. ASR expansion assessment

A series of test was conducted to assess the ASR reactivity of different particles size of glass used in both wet-mixed and dry-mixed mortar bars and the effectiveness of pozzolanic materials in reducing the ASR expansion.

Measurement of ASR expansion of mortar bar according to ASTM C1260

An accelerated mortar bar test was carried out on three prism specimens of 25×25×285 mm in accordance with ASTM C1260. After 28 days of water cured, the mortar bar specimens were removed from water tank and stored in distilled water at $80^{o}C$ for another 24 hours at which a zero reading was taken. The bars were then transferred and immersed in 1 N NaOH solution at 80 °C until the testing time at 1, 4, 7, 14 and 28 day. The expansion of the mortar bars was measured within 15±5 seconds after the mortar bars were removed from the 80 °C distilled water or alkali storage condition by using a length comparator.

Flexural strength of mortar bar

Flexural strength of mortar bar specimens was determined to complement the results of the ASR expansion test. Before and after the ASR test, the flexural strength test was carried out under a central line load simply supported over a span of 120 mm and displacement rate of 0.05 mm/min was applied.

SEM analysis

After the mechanical testing, some samples were selected to examine the microstructure as well as nature of the binder-glass interfacial zone. The fragmented samples were immersed in acetone for 4 hours and dried in a vacuum oven in order to eliminate any free water and stop the progress of hydration as well as chemical reaction. The samples were then gold coated and analyzed in a Scanning Electron Microscopy (SEM) operated at an accelerating voltage of 20kV with a probe current of 70 to 78 μA.

Chapter 4 - Effects of Recycled Fine Glass Aggregates on the Properties of Dry-Mixed Concrete Blocks

4.1.Introduction

In this chapter, the effects of different replacement percentages and particle size distributions of fine glass on the properties of dry-mixed concrete blocks have been investigated. The effect of different particle size of glass on water demand, packing volume ratio, hardened density and water absorption properties of the concrete block were discussed supported by systematic test results. Furthermore, effects of air and water curing on the 7 and 28 day compressive strength of the blocks were also examined.

4.2. Test results and discussion

4.2.1. Fineness modulus of fine aggregate and water demand

The optimum water–cement (W/C) ratio required for each concrete block mixture was determined based on the workability required for the dry-mixed concrete (with sufficient water to achieve a cohesive mix but with no slump). Figure 4.1 displays the relationship between the required W/C ratio and fineness modulus of fine aggregate. The required W/C ratio was found to be inversely proportional to the fineness modulus In order to achieve the same cohesiveness for the dry-mixed mixtures, fine aggregate with lower FM required larger amount of water and this trend is similar to those reported in the literature. Chang et al. (2001) have stated that when the fineness modulus of fine aggregate is reduced, more water is required to maintain the workability of fresh concrete.

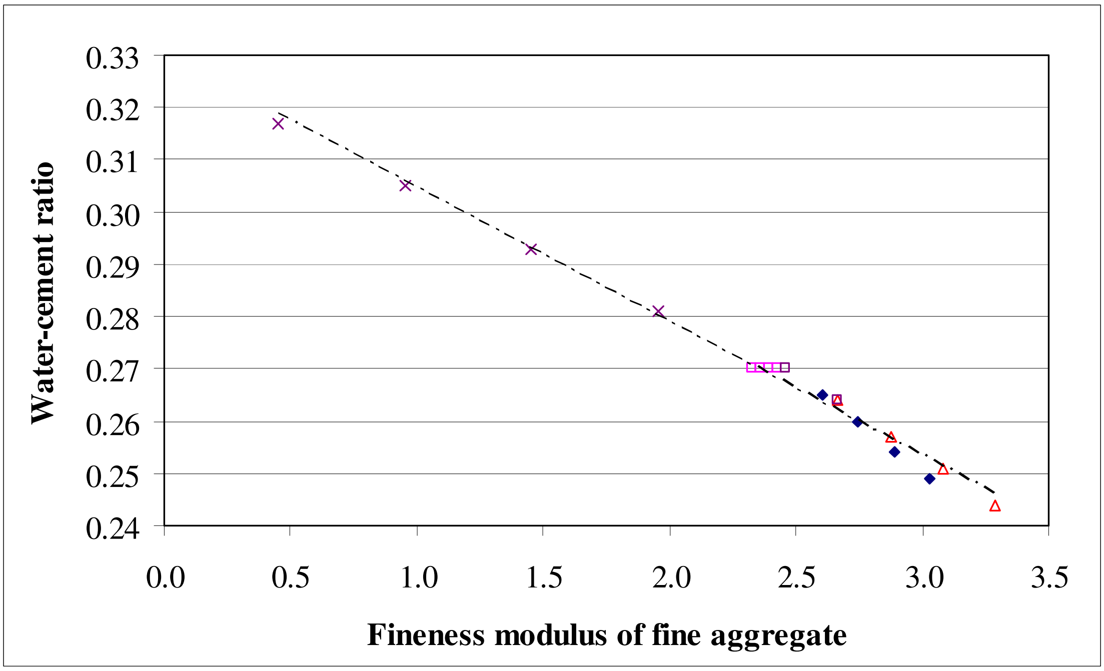


Figure 4.1: Effect of fineness modulus of fine aggregate on the W/C ratio

4.2.2. Effect of particle sizes on packing volume ratio of aggregates

The relationships between fine glass parameters and the packing volume ratio of aggregates are shown in Figure 4.2. Overall, incorporating A-FG, B-FG and C-FG as fine aggregate improved the packing volume ratio. Comparing these data, it is evident that no combination seems to have significant effect on the packing volume ratio, while the packing volume ratio decreased significantly with the incorporation of the finer glass (D-FG). As seen in Figure 4.2, the packing volume ratio by incorporating 25%, 50%, 75% and 100% of D-FG were 0.739, 0.719, 0.682 and 0.646, respectively. The main reasons for this could be the narrower of the particle size distribution with the reduction of particle size that results in an uniform particle distribution of very fine glass particles within D-FG.

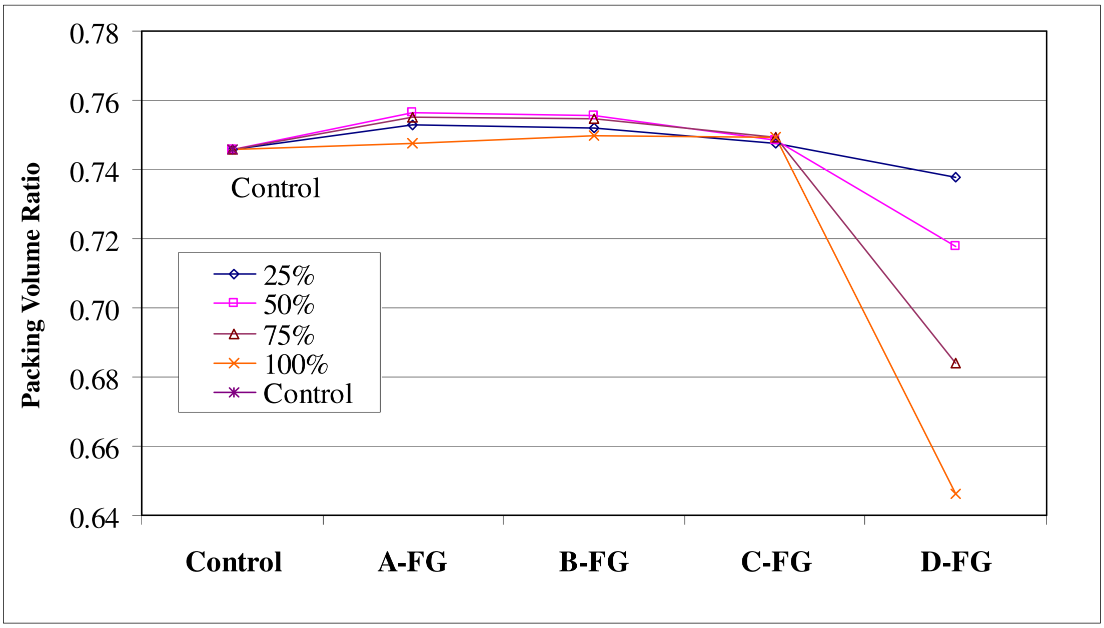


Figure 4.2: Effect of particle sizes on the packing volume ratio

4.2.3. Effect of particle sizes on the hardened density

Figure 4.3 illustrates the effects of different particle sizes of the FG on the hardened density of dry-mixed concrete blocks. Irrespective of the influence of particle size, increase of FG content in the concrete blocks decreased the hardened density. The reason was that FG had a lower specify gravity than that of sand. Previous research has indicated that the addition of waste glass aggregate results in a linear decrease of concrete density (Park et al., 2004).

Apart from glass content, it is important to note that the hardened density of all concrete block mixes decreased with decreasing particle size of the FG. As shown in Figure 4.3, the trend is less obvious in the cases of A-FG, B-FG and C-FG when compared to D-FG. The maximum decrease of the hardened density occurred when 100% of sand was replaced by D-FG. This can be explained partially, by the poor packing of the uniformly graded very fine particles. This is consistent with the results shown in Figure 4.2.

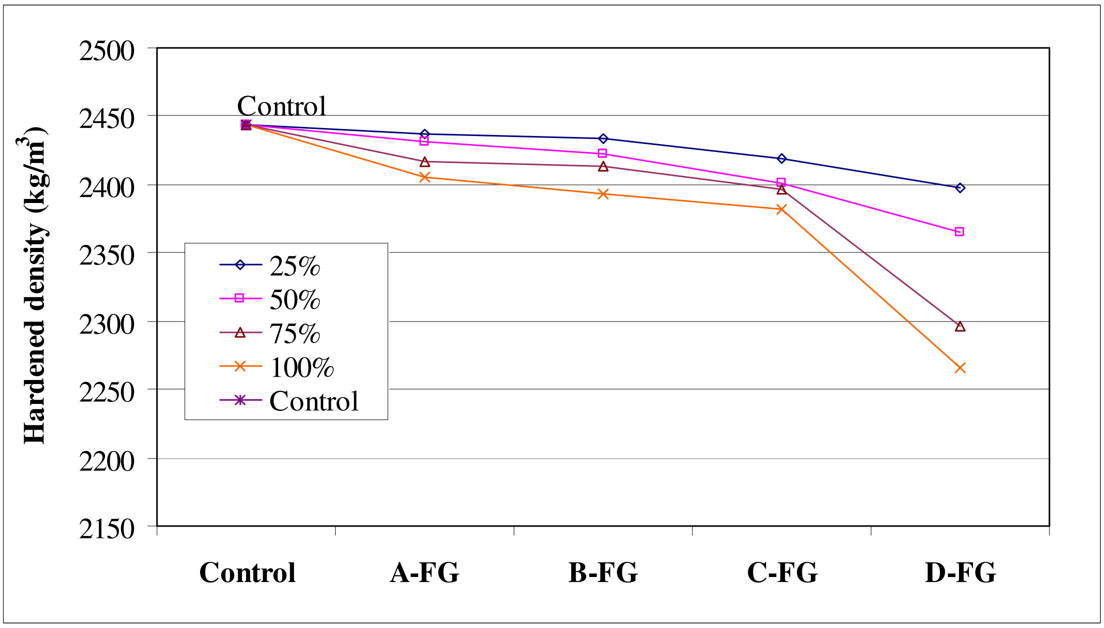


Figure 4.3: Effect of fine glass parameters on the hardened density of concrete blocks

4.2.4. Effect of particle sizes on the water absorption

The results of water absorption of the blocks are presented in Figure 4.4 which indicates that, concrete blocks containing FG as aggregate had higher water absorption values when compared to that of the control. An increase in glass content increased the water absorption. These results are similar to that of Park et al. (2004) who have reported that the water absorption of concrete made with waste glass was slightly higher than the control concrete block. Further reducing the particle size of FG to less than 600µm, the water absorption markedly increased from 4.68 to 6.43 when the glass content was increased from 25% to 100%. These results are related to the results of the packing volume ratio of the aggregates and the hardened density of the blocks discussed above.

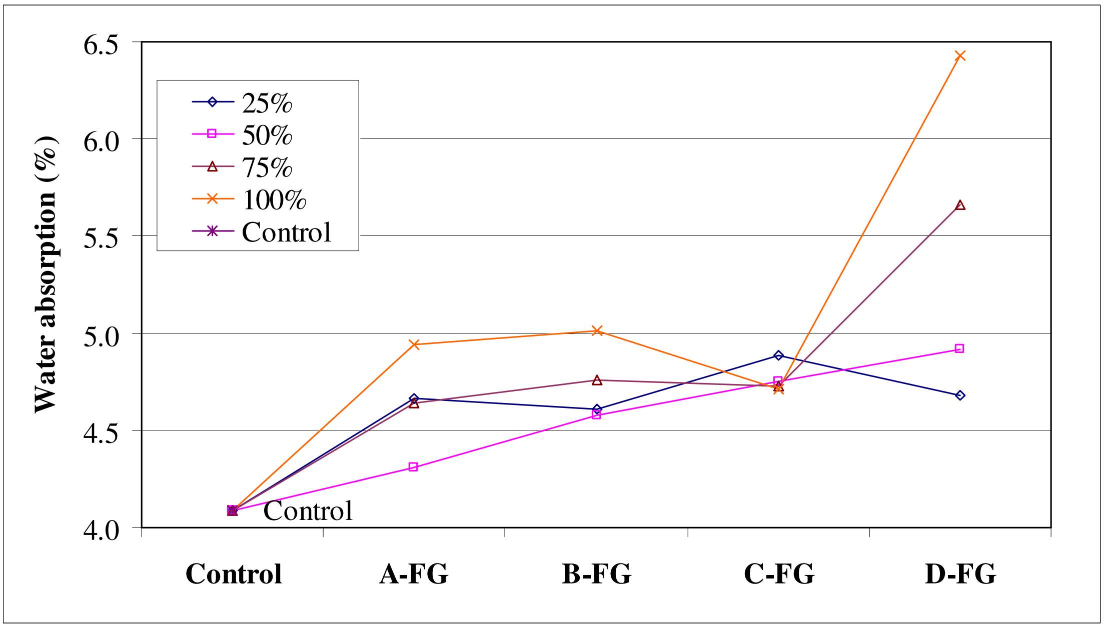


Figure 4.4: Effect of particle sizes on the water absorption of concrete blocks

4.2.5. Effect of particle sizes on the compressive strength

Figure 4.5 shows the results of the 28-day compressive strength of concrete block versus different particles sizes of FG used. It can be seen that inclusion of FG as a sand replacement in concrete block mixes had a negative effect on the compressive strength, with the exception of D-series. Furthermore, it should be noted that the effect of varying FG content on the compressive strength of A, B and C-series of concrete blocks was not significant when compared with the D-series of concrete blocks. In fact, in A-series, concrete block mixtures with 25% of un-sieved particle size of fine glass, an approximately 8.8% reduction in 28-day compressive strength was noticed. When the A-FG content increased to 100%, the reduction in 28-day compressive strength reached

11.5%. Similar results were also obtained for concrete block mixtures mixed with B-FG and C-FG.

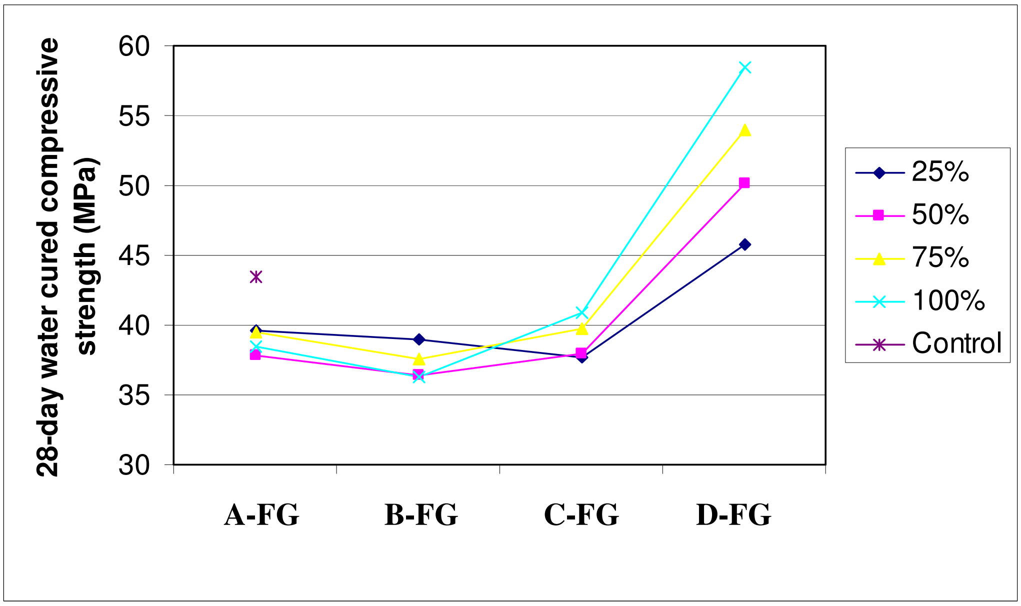


Figure 4.5: 28-day water cured compressive strength of concrete blocks (effect of particle size)

From these results it can be inferred that FG in the range of un-sieved to those of <1.18mm (within A, B and C-series) exerted very little effect on the compressive strength of the blocks. The key reason of reduction in strength with the inclusion of the coarser FG may be attributed to the decrease in bond strength between the glass particles and the cement paste due to their smooth and impermeable surface (Kou and Poon, 2009). Since the FG particles were produced by crushing waste glass bottles, it is possible for the glass particles to contain micro-cracks. This could also lead to reduced strength due to further internal cracking upon loading. Besides, the concrete blocks containing FG particles had higher water absorption values and in other words, a higher void content which would also reduce the compressive strength.

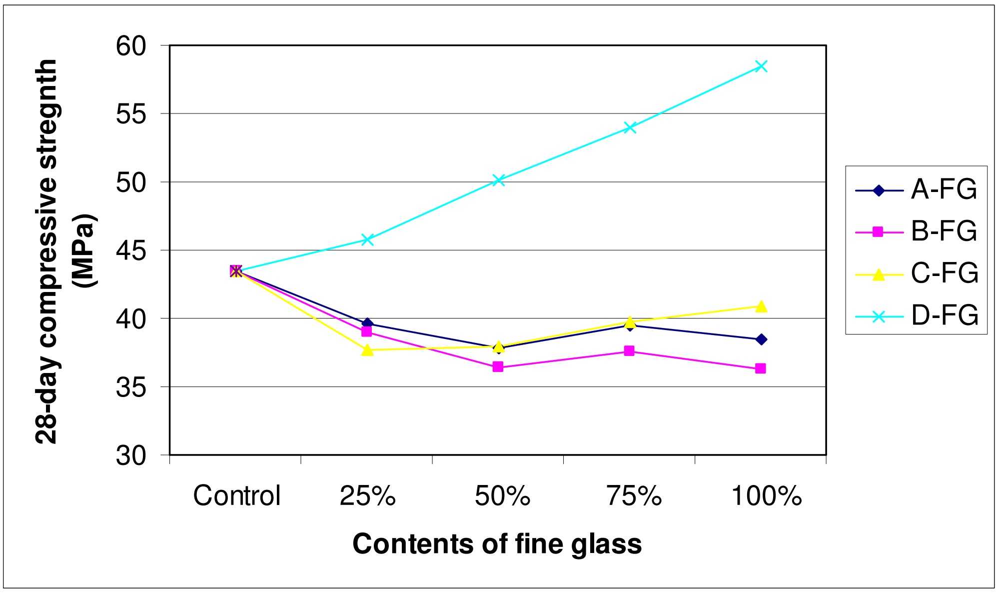


Figure 4.6: 28-day water cured compressive strength of concrete blocks (effect of replacement percentage of FG)

As seen in Figure 4.6, all the mixes in the D-series show higher compressive strength than that of the others. It can be seen that, there was a systematic increase in compressive strength as the D-FG content increased despite the fact that the D-series of concrete block mixtures showed a decreasing trend in the packing volume ratio and hardened density. The improvement in the 28-day compressive strength could be attributed to the pozzolanic reaction of the very fine D-FG particles. It has been reported that the strength activity indices of fine glass powder with particle sizes ranging from 40 to 700µm were 70% to 74% at 7 and 28 days, respectively (Shi et al., 2005). Therefore, it appears that the pozzolanic effect outweighed the poorer packing volume ratio effect for the D-series concrete blocks.

4.2.6. Effect of air and water curing on compressive strength

The 7-day and 28-day compressive strength of the dry-mixed concrete blocks cured under air and water conditions are presented in Table 4.1. In general, the compressive strength increased with time for both curing conditions. The percentage increase in compressive strength of the C and D-series concrete blocks was higher than that of the A and B-series blocks.

Table 4.1: 7 and 28-day compressive strength of dry-mixed concrete blocks

Mixtures	7- day compressive strength (MPa)		28-day compressive strength (MPa)		% difference between 28-day air and water cured strength
	Air cured	Water cured	Air cured	Water cured	
Control	34.21	34.33	41.65	43.51	4.5
A-25	31.25	31.69	37.42	39.67	6.0
A-50	30.82	31.26	35.73	37.87	3.0
A-75	34.49	35.60	37.32	39.55	5.1
A-100	33.21	34.75	35.20	38.49	9.2
B-25	32.48	32.58	37.77	38.92	6.0
B-50	31.32	32.07	35.38	36.46	3.1
B-75	34.66	35.52	36.50	37.61	8.2
B-100	32.38	33.37	35.14	36.22	14.0
C-25	28.60	28.77	35.88	37.72	6.0
C-50	29.20	29.42	35.03	37.91	3.0
C-75	27.88	29.33	34.22	39.76	16.2
C-100	29.47	31.25	33.76	40.96	18.7
D-25	37.67	37.14	41.86	45.72	9.3
D-50	38.85	39.02	43.96	50.10	3.1
D-75	40.46	41.42	45.50	54.02	21.3
D-100	36.26	39.46	44.80	58.44	30.4

* Relative difference = (water-air)/water

When the 7 and 28-day compressive strength of the air cured blocks (100% sand replacement) were compared with those cured in water and the percentages increase are shown in Table 4. This indicates that water curing enabled significant pozzolanic reaction to take place for the D-FG blocks (Shao et al., 2000; Shi et al., 2005).

4.3. Conclusions

Based on the above results, the following conclusions can be drawn

1. A higher W/C ratio was required for the block mixtures to achieve the same cohesiveness when the fineness modulus of fine aggregates was reduced. The Packing volume ratio reduced as very fine FG was incorporated due to the uniform particle size distributions. The hardened density of the concrete blocks decreased with the increase in the FG because of the lower specific gravity of FA. The replacements of sand by FG increased the water absorption of dry-mixed concrete blocks. The influence of FG content on water absorption clearly seemed more pronounced when finer FG was used.
2. Inclusion of the very fine FG increased the compressive strength of concrete blocks due to its pozzolanic reactivity. The effect of water curing was more pronounced for blocks made with the finer FG.

Chapter 5 - Effect of Fine Glass Aggregate on the Mechanical Properties of Wet-Mixed Concrete Blocks

5.1. Introduction

In this chapter, the effects of different particle size distribution of fine glass as well as its potential use as a partial or full replacement as fine aggregate in the production of wet-mixed concrete blocks were investigated and the findings are presented and discussed.

The packing volume ratio, hardened density and water absorption properties of the concrete block composites were investigated. The affects of air and water curing conditions on the 7 and 28 day compressive strength were studied.

5.2. Results and discussion

5.2.1. Effect of particle size of FG on the hardened density

The relationships between particle size of FG at different replacement percentages and the hardened density of wet-mixed concrete blocks are presented in Figure 5.1 which reveals that the hardened density of concrete block reduced with the increase of FG content, and reduced with the reduction of particle size of FG.

In series-D, with the increase of the FG content from 25% to 100%, the hardened density was reduced by 1.6%, 2.4%, 2.5% and 6.5% comparing with control. The reason for this was because FG glass had a lower specific gravity than that of sand. Therefore, the higher the content of FG in a unit weight volume of the concrete block mixture, the lighter was the hardened density of the concrete block.

The hardened density of all concrete block mixes decreased with the reduction of particle size of FG. For 100% FG in concrete blocks, the hardened density was reduced significantly for series C and D. Apart from smaller density of FG, the poor packing effect of the aggregates due to the uniform grading of very fine FG was also the reason.

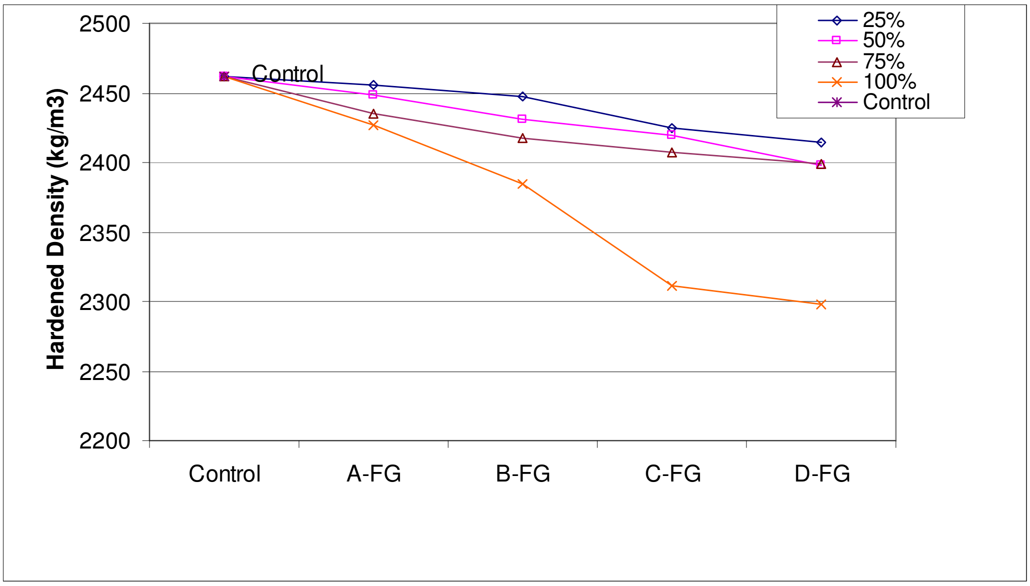


Figure 5.1: Effect of fine glass parameters on the hardened density of concrete blocks

5.2.2. Effect of particle size of FG on water absorption

The results of water absorption of the blocks are presented in Figure 5.2. With the decrease in particle size of FG from A-FG to D-FG, the water absorption increased significantly. For D-FG (<600µm), the water absorption markedly increased from 4.70 to 6.45 when the FG content was increased from 25% to 100%.

The concrete blocks containing FG as fine aggregate had higher water absorption values than the control. It was due to the fact that fine glass aggregates were irregular in shape, which resulted poor packing of aggregates. These results are similar to that of Park et al.

(2009) who reported that the water absorption of concrete made with waste glass was slightly higher than the control concrete block.

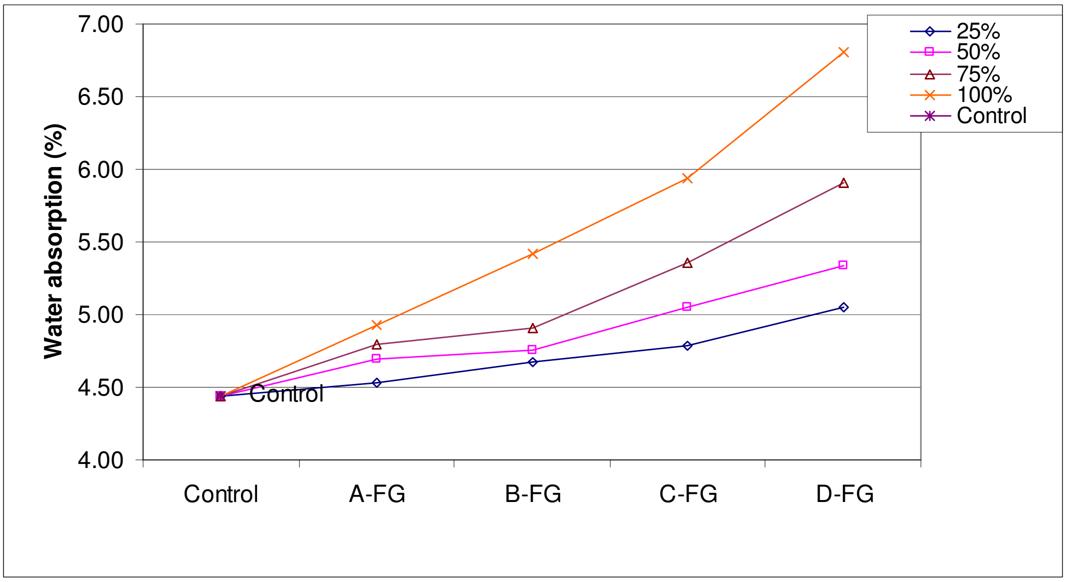


Figure 5.2: Effect of fine glass parameters on the water absorption of concrete blocks

5.2.3. Effect of particle size of FG on the compressive strength

The results of the 28-day compressive strength of concrete blocks are presented in Figure 5.3. It can be observed that using fine glass (FG) to replace sand in concrete block mixes led to a reduction on the compressive strength. The reduction percentages were higher with the use of finer FG (Un-sieved to those less than 1.18mm) and increased of FG content. When the replacement percentage was 100%, the reduction of strength of A-FG, B-FG and C-FG were 11.9%, 20.9% and 25.9% respectively. The reasons for the strength reduction are due to the decrease of bond strength between the glass particles and the cement paste due to the impermeable and smooth surface of glass (Kou and Poon, 2009). FG are produced by crushing waste glass bottles. During the crushing process, initial cracks might have been produced which could also lead to a reduced bond due to further internal cracking. In addition, concrete blocks containing fine glass particles had greater water absorption which meant that it had a higher void content which also led to the reduction of concrete strength.

It could be noted that the strength reduction of concrete blocks of series D (<1.18mm FG) was 31% which was a little smaller than series C (<0.6mm FG). This improvement could be attributed to pozzolanic reaction of D-FG with glass particle size <600μm. (Shi et al., 2005)

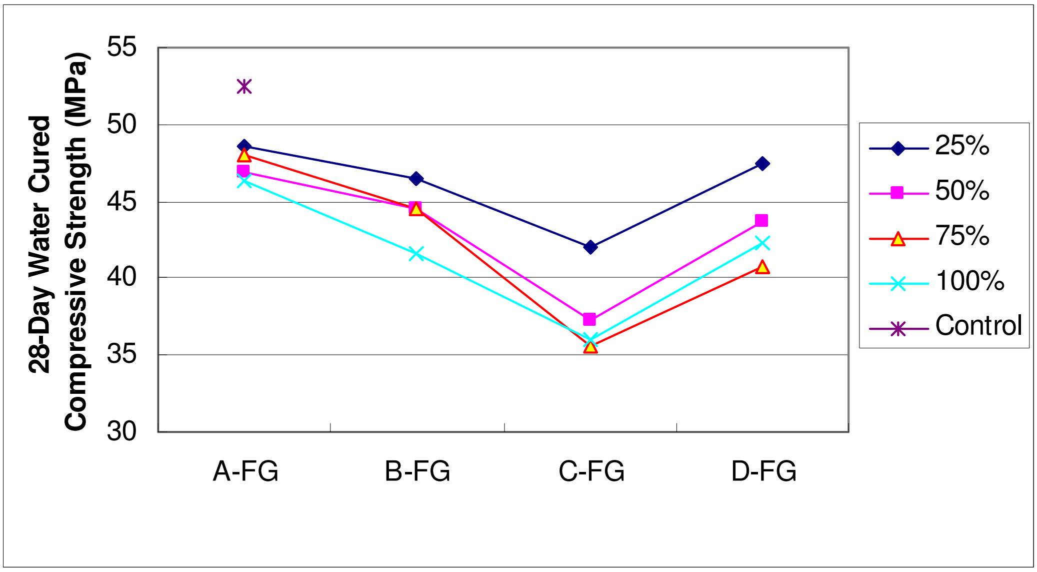


Figure 5.3: 28-day water cured compressive strength of concrete blocks versus different particle size of FG

As seen in Figure 5.3 and Figure 5.4, all the mixes in the D-series show higher compressive strength than that of C-series and similar to that of B-series. It can be seen that, there was a systematic increase in compressive strength comparing with C-FG despite the packing volume ratio and hardened density of D-series were smaller than C-series. The improvement in the 28-day compressive strength could be attributed to the pozzolanic reaction of the very fine D-FG particles. Shi et al. (2005) reported that the strength activity indices of fine glass powder with particle sizes ranging from 40 to 700 μm were 70% to 74% at 7 and 28 days. Therefore, it appears that the pozzolanic effect partially ourweighed the poorer packing volume ratio effect for the D-series concrete and led to the enhancement of compressive strength.

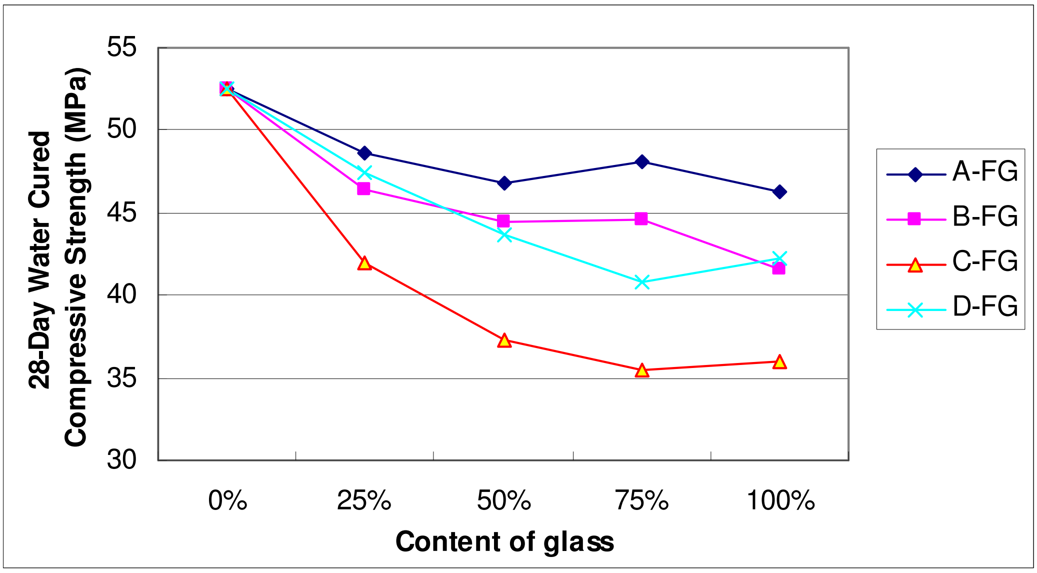


Figure 5.4: 28-day water cured compressive strength of concrete blocks versus different contents of FG

5.2.4. Effect of water curing on concrete blocks with different particle size FG

The 7-day and 28-day compressive strength of the wet-mixed concrete blocks cured under air and water conditions are presented in Table 5.1. In general, the compressive strength increased with time for both curing conditions. Obviously, the strength increment of concrete block was larger with the reduction of particle size of FG from A-FG to D-FG.

When the 7 and 28-day compressive strength of the air cured blocks (100% replacement) were compared with those cured in water, the percentages increase of control, series-A, B, C and D were 15.99%, 19.%, 11.10%, 41.44% and 53.27% respectively. It was obvious that the percentages increases of compressive strength of concrete blocks was larger with finer FG was used as fine aggregate. This indicates that water curing had an important role on pozzolanic reaction to take place for concrete containing fine FG (Shao et al., 2000; Shi at el., 2005).

Table 5.1: 7 and 28-day compressive strength of wet-mixed concrete blocks

Mixtures	7- day compressive strength (MPa)		28-day compressive strength (MPa)		% different between 28-day air and water cured strength
	Air cured	Water cured	Air cured	Water cured	
Control	32.13	37.39	45.29	52.53	15.99
A-25	29.23	33.59	41.13	48.65	18.27
A-50	26.81	32.40	41.51	46.86	12.89
A-75	27.02	34.22	40.42	48.08	18.96
A-100	26.55	31.02	38.82	46.31	19.28
B-25	27.37	32.22	40.85	46.45	13.71
B-50	25.88	30.80	38.88	44.48	14.41
B-75	26.46	30.12	39.49	44.52	12.74
B-100	26.56	29.84	37.40	41.55	11.10
C-25	25.11	27.11	35.09	41.96	19.56
C-50	20.38	25.95	30.37	37.24	22.61
C-75	21.22	24.71	29.67	35.52	19.72
C-100	18.18	25.16	25.49	36.05	41.44
D-25	22.85	30.10	32.61	47.44	45.48
D-50	20.84	27.44	29.61	43.67	47.48
D-75	19.42	28.12	24.51	40.80	66.46
D-100	21.73	29.31	27.55	42.23	53.27

* Relative difference = (water-air)/water

5.3. Conclusions

The following conclusions are drawn based on the results of wet-mixed concrete block mixtures containing different content and particle size of fine glass:

1. Packing volume ratio reduced as very fine FG was incorporaed due to the uniform particle size distributions of FG.
2. The hardened density of concrete blocks decreased by increasing the FG content because of the lower specific gravity of FG.
3. The replacements of sand by FG increase the water absorption of wet-mixed concrete blocks. The influence of FG content on water absorption is more pronounced when finer fine glass was adopted.
4. Inclusion of FG replacing sand led to the decrease of compressive strength of concrete blocks due to the weak bonding between particle glass and cement paste. The percentage of strength reduction of D-series (particle size of FG <600μm) was smaller than C-series (particle size of FG <1.18mm) it was because the pozzolanic reaction of very fine FG was stronger than coarse FG so that it partially compensate the negative effect.
5. The effect of water curing was more pronounced for blocks with finer FG due to the pozzolanic activity of finer FG is higher which need larger amount of water for pozzolanic reaction.

Chapter 6 - Studies on the Reduction of ASR Expansion: Influence of Using Different Particles Size of Glass, Casting Methods and Pozzolanic Materials

6.1.Introduction

This chapter presents the findings on using different particles size of recycled glass, casting methods and pozzolanic materials in reducing the expansion due to alkali-silica reaction (ASR). In addition, the influence of fly ash and metakaolin content on the reduction of ASR expansion was also investigated. Flexural strength of mortar bar specimens before and after exposed to 1 N NaOH solution was determined to justify the results of ASR expansion. The SEM and EDX were performed to examine the microstructure as well as nature of the binder-glass interfacial zone.

6.2. Test results and discussion

6.2.1. Effect of particle size of recycled glass on ASR expansion

Average ASR expansion results of mortar bars prepared with different particles size of glass obtained from rapid test method at 14 and 28 days are shown in Figure 6.1. The results show that in all cases, the wet-mixed ASR expansion is higher than that of the dry-mixed ASR expansion. Regardless of particle size of glass, all the ASR expansion of dry-mixed mortar bars is found to be within the permissible limit of 0.1% at 14 days. However, the wet-mixed mortar bars prepared with FG-A and FG-B is found to be above this limit set by ASTM C 1260. It is also noticed that there was an increase of approximately 8% and 28% in average of ASR expansion when the wet-mixed and dry mixed mortar bars were allowed to be exposed in the aggresive environment (1 N NaOH alkali solution) for the further 14 days.

From the Figure, it can be clearly observed that the ASR expansion decreases with the decrease of particle size of glass, and it becomes more significant when the particle size of glass was less than 600 μm. This implies that finely glass particles can mitigate ASR expansion (Zhu et al., 2009). Therefore, it is important to note that if recycled glass containing high content of active silica can be classified as a reactive aggregate or a pozzolanic material, depending on its particle size. The ASR expansion of wet-mixed mortar bars dec by 18.3%, 26.2% and 49.2% when WM-B, WM-C, and WM-D are compared to WM-A at 14 days. The ASR expansion of dry-mixed mortar bars were reduced by 3.4%, 10.2% and 30.0%. When DM-B, DM-C, and DM-D are compared to DM-A at 14 days. This concludes that the influence of particle size of glass on wet-mixed mortar bars was more pronounced than that of the dry-mixed mortar bars.

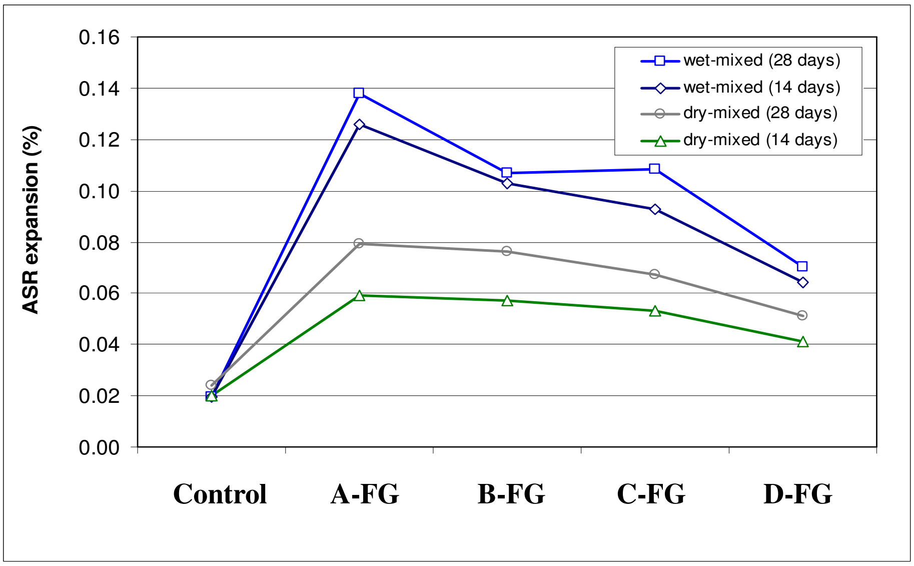


Figure 6.1: Effect of different particles size of glass on ASR expansion at 14 and 28 days

6.2.2. Influence of PFA and MK on ASR expansion

Figure 6.2 and Figure 6.3 show the influence of PFA and MK content on the ASR expansion at 14 and 28 days, respectively. It can be seen that the ASR expansion rates noticeably decreased with an increase in PFA and MK content regardless of the particle size of recycled glass used. This could be due to the pozzolanic reaction leads a formation of low C/S and the C-S-H gel that is able to adsorb alkalis and that subsequently leading to the reduction of ASR expansion (Topcu et al., 2008). A comparison of efficiency of PFA and MK on ASR expansion of mortar bars prepared with different particles size of glass are also included in Figure 6.2 and Figure 6.3. It is found that when the amount of FPA is at 5%, the ASR expansion at 14 days was reduced to the range of 0.028% to 0.035% regardless of the particle size of glass used. However, as the amount of PFA increased to 10% and 20%, there was insignificant change in ASR expansion. On the other hand, as the amount of MK was increased from 0% to 5%, 10% and 20%, there was a gradual reduction in ASR expansion by approximately 14.2%, 29.3% and 47.2%, respectively, regardless of the particle size of glass used.

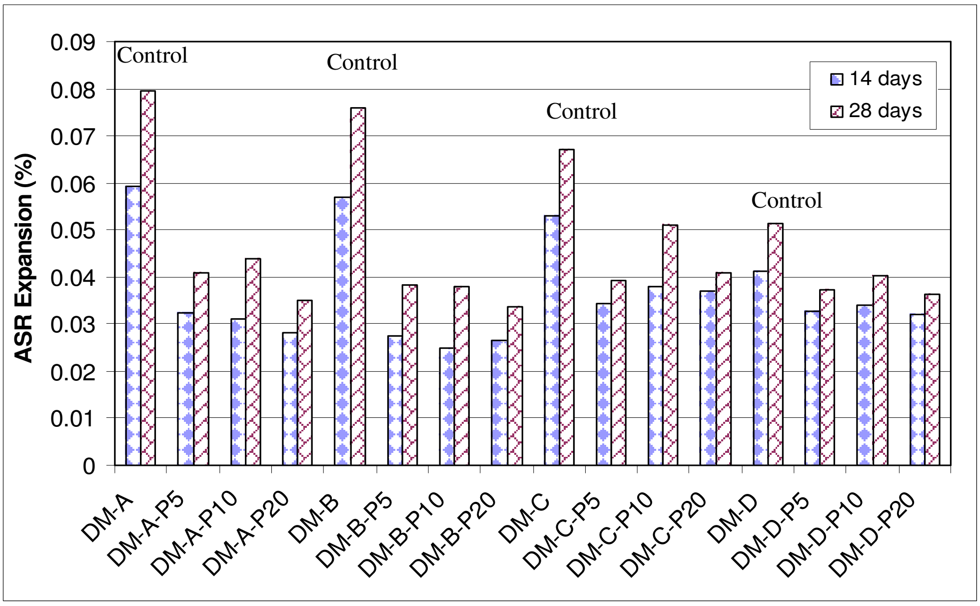


Figure 6.2: Influence of PFA content on the ASR expansion at 14 and 28 days

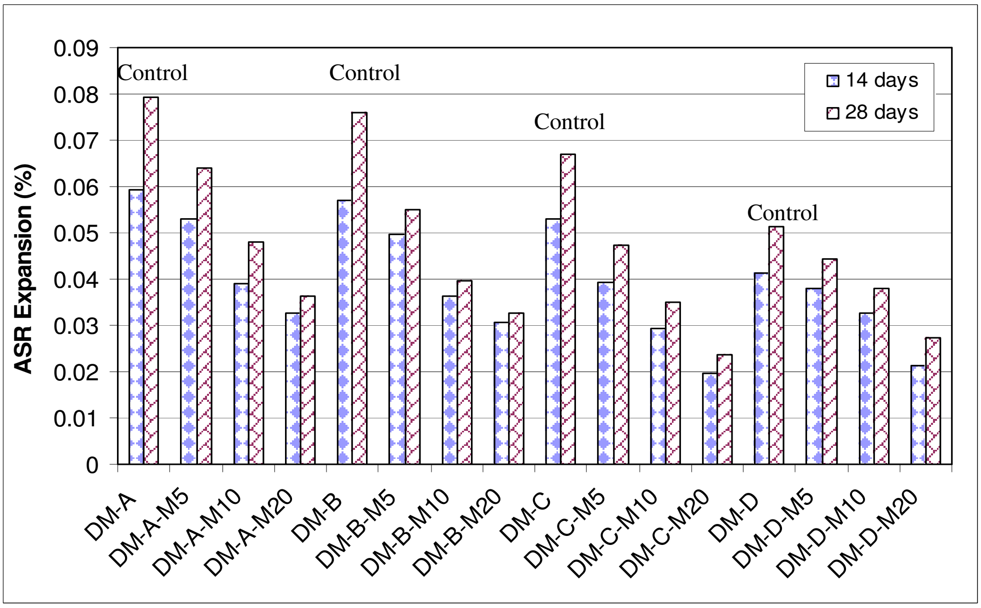


Figure 6.3: Influence of MK content on the ASR expansion at 14 and 28 days

Figure 6.4 shows the results of the effectiveness between PFA and MK in reducing the ASR expansion at 14 days. It is worth to note that the expansion reduction of mortar bars containing PFA was clearly higher than that of mortar bars containing MK in the case of 5%. This indicate that at a lower content of pozzolanic materials used, PFA is found to be more effective than MK in reducing the expansion due to ASR. However, as the PFA and MK contents were increased to 20%, for any given mix proportion, the effectiveness on the reduction of ASR expansion were quite similar.

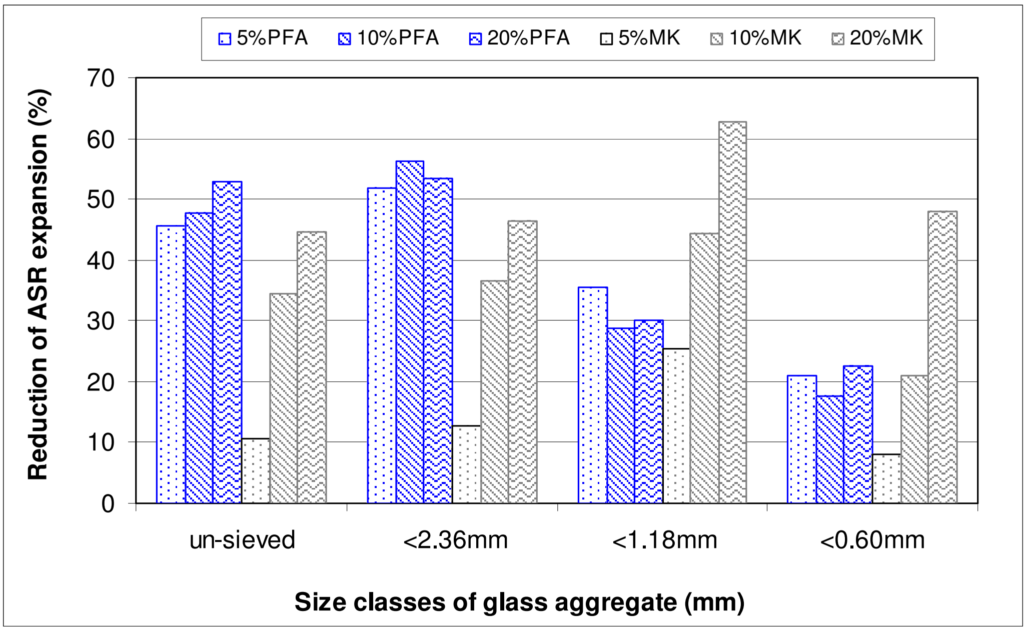


Figure 6.4: Comparison of PFA and MK on the reduction of ASR expansion at 14 days

6.3. Conclusions

Based on the experimental test results, the following conclusions can be drawn:

1. The reduction of ASR expansion increase with the decrease of particle size of glass, and it becames more significant when the particle size of glass used was less than 600 μm.
2. Both PFA and MK can effectively mitigate ASR expansion regardless of the particle size of glass used. The reduction of ASR expansion of mortar bars containing PFA was clearly more effective than MK in the case of 5%. However, at higher content at 20%, both FPA and MK show similar effectiveness in suppressing ASR expansion.

Chapter 7 – Comparison of Effects of Recycled Fine Glass Aggregate on the Properties of Dry-mixed and Wet-mixed Concrete Blocks and the ASR Expansion of Dry-mixed and Wet-mixed Mortar Bars

7.1. Introduction

In chapter 4 and 5, the effects of different size of recycled fine glass (FG) on the properties of dry-mixed and wet-mixed concrete blocks were studied respectively. In chapter 6, the effects of different size of recycled fine glass (FG) on the ASR expansion of dry-mixed and wet-mixed mortar bars were also studied.

In this chapter, the comparison on the properties and ASR expansion between dry-mixed and wet-mixed concrete blocks/mortar bars are presented.

7.2. Comparison of properties of dry-mixed and wet-mixed FG concrete blocks

7.2.1. Hardened Density and Water Absorption

The effects of adding FG on the hardened density and water absorption of fresh concrete mixture of dry-mixed and wet-mixed concrete blocks were similar. According to Figure 7.1, the hardened density of both dry-mixed and wet-mixed concrete blocks containing 75% FG content decreased with the increase of FG content, and reduction of particle size of FG. It was because glass had a lower density than sand. Moreover, when the finer FG was used in the concrete mixtures, the packing volume ratio decreased which also led to the increase of void content and reduction of hardened density due to the irregular shape of glass particle and uniform grading. The water absorption increased with the reduction of particle size of FG due to the increase of void content in the concrete blocks.

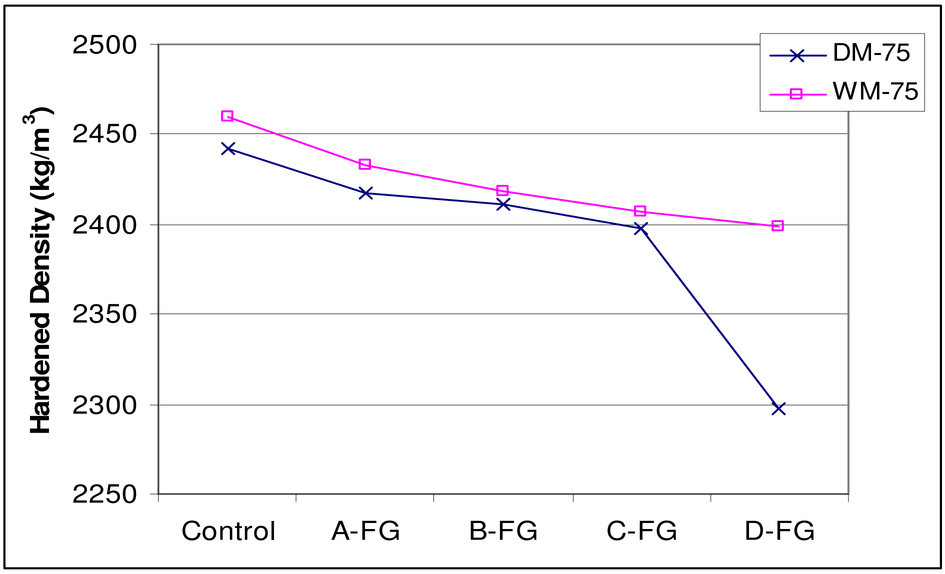


Figure 7.1: Hardened density of concrete blocks DM-75 and WM-75

In general, the hardened density of wet-mixed concrete block was higher than that of dry-mixed concrete blocks. It was because the wet-mixed concrete mixture obtained a better compaction than dry-mixed concrete during mixing which led to a less void content. In Figure 7.2, the SEM images showed that more void content was found in dry-mixed concrete blocks comparatively which resulted in a lower hardened density.

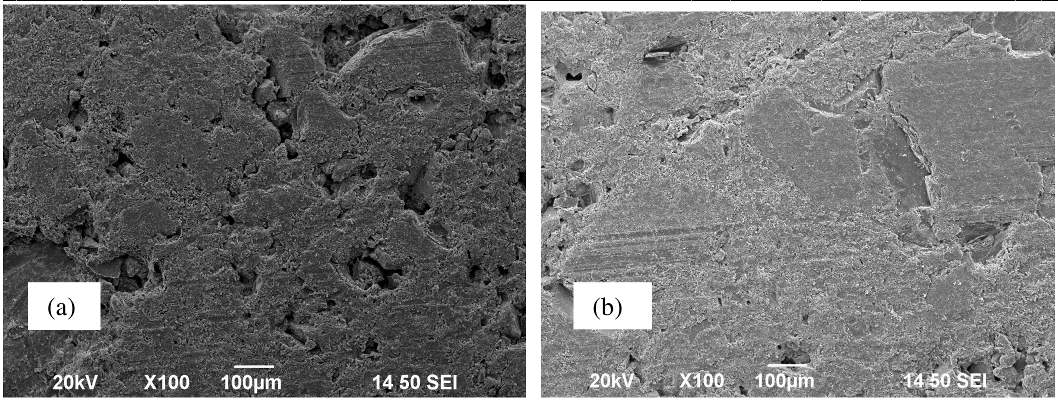


Figure 7.2: SEM image of concrete blocks DM-A-100 (a) and WM-A-100(b)

7.2.2. Compressive Strength

The compressive strength decreased with the use of finer FG (Un-sieved up to 1.18mm) for both dry-mixed and wet-mixed concrete blocks. According to Figure 4.5 and Figure 5.3, the percentage reductions of strength of the wet-mixed concrete blocks were larger than that of the dry-mixed concrete blocks. It was because water and air may be trapped in the surface of the irregularly angled glass particles. (Park et al., 2004) With the reduction of particle size of FG, the surface area of FG was increased and the water and air content which would be possibly trapped on the FG content were increased. The SEM image of interfacial transition zone (ITZ) of WM-C-100 and DM-C-100 are presented in Figure 7.3 and Figure 7.4 respectively. In Figure 7.3, lots of voids are found around the surface of glass particles because excess water accumulated around the surface of glass particles and evaporated after the concrete was set. In Figure 7.4, no voids are found between cement paste and glass particle in dry-mixed concrete blocks.

For the dry-mixed concrete blocks, the water and air content that were trapped in the glass particles were believed to be partially squeezed out during the process of fabrication by a large external compressive force on the concrete mixtures. As the results, this negative effect on compressive strength was less in the dry-mixed concrete blocks. For both the dry-mixed and wet-mixed concrete blocks, the compressive strength of D-series (<600μm) was higher than that of C-series (<1.18mm) due to the pozzolanic effect of very fine glass which is beneficial on the compressive strength.

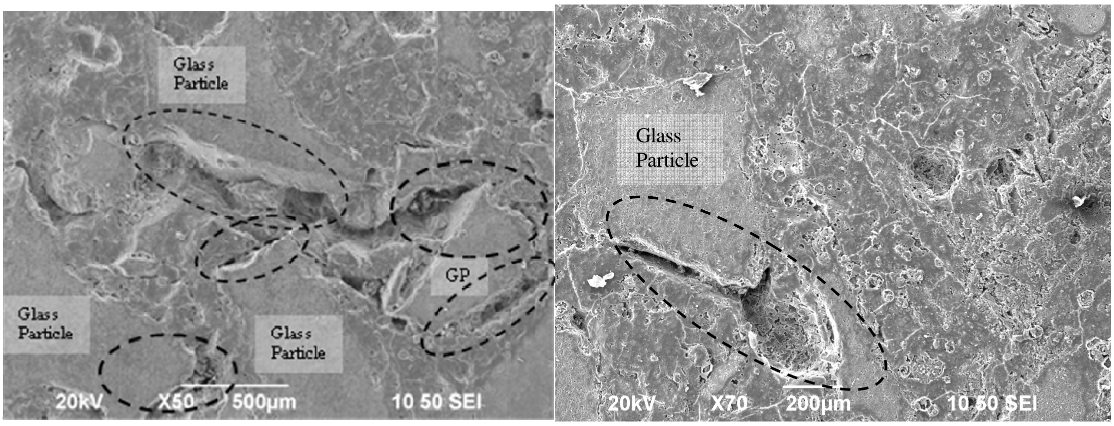


Figure 7.3:SEM image of ITZ of cement paste and glass particle of WM-C-100 (x50)

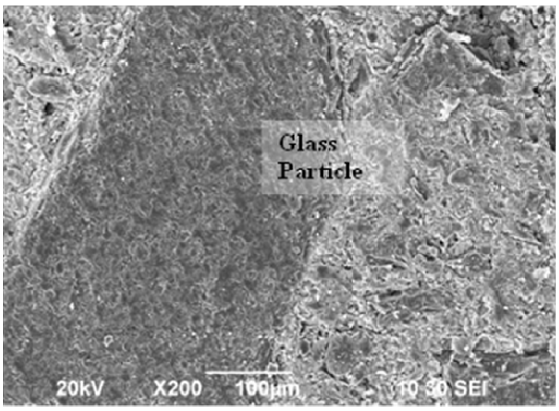


Figure 7.4: SEM image of ITZ of cement paste and glass particle of DM-C-100 (x200)

7.2.3. Effect of Water Curing on Compressive Strength

Table 7.1 presents the percentage difference between 28-day air and water cured compressive strength of dry-mixed and wet-mixed concrete blocks. It is obvious that the effect of water curing on the wet-mixed concrete was larger than that of the dry-mixed concrete. It was because more capillary pores around the pozzolanic FG particles in wet-mixed concrete which served as a path for water to approach as a necessary component for pozzolanic reaction.

Table 7.1: Percentage difference between 28-day air and water cured compressive strength of dry-mixed and wet-mixed concrete blocks

Concrete mix	% difference between 28-day air and water cured compressive strength of dry-mixed concrete blocks	% difference between 28-day air and water cured compressive strength of wet-mixed concrete blocks
Control	4.5	15.99
A-25	6.0	18.27
A-50	3.0	12.89
A-75	5.1	18.96
A-100	9.2	19.28
B-25	6.0	13.71
B-50	3.1	14.41
B-75	8.2	12.74
B-100	14.0	11.10
C-25	6.0	19.56
C-50	3.0	22.61
C-75	16.2	19.72
C-100	18.7	41.44
D-25	9.3	45.48
D-50	3.1	47.48
D-75	21.3	66.46
D-100	30.4	53.27

7.2.4. Comparison of wet-mixed and dry-mixed (casting) method on ASR expansion

Effect of dry-mixed (casting) method on the reduction of ASR expansion of mortar bars incorporating different particles size of glass is shown in Figure 7.5. The results show that using dry-mixed method was very efficient in reducing the ASR expansion especially for larger particle size (highly reactive) glass aggregate. The reduction of ASR expansion at 14 days were 53.2%, 44.7%, 43.0% and 35.5% for the mortar bar containing 100% recycled glass of FG-A, FG-B, FG-C and FG-D, respectively.

Several reasons may be contributing to this behaviour which is explained in the following. For a same mix proportion, the water cement ratios of dry-mixed mortar bars is lower than that of the wet-mixed mortar bar which means very small amount of water is available in the mortar to form ASR gel. Another possible explanation is that the mortar bars made by the dry-mixed method contains higher porosity and larger capillary pores (see Figure 7.6a), thus, they are able to accommodate larger amount of ASR gel (see Figure 7.6b), resulting lower expansion and cracks when compared to mortar bars made with the wet-mixed method.

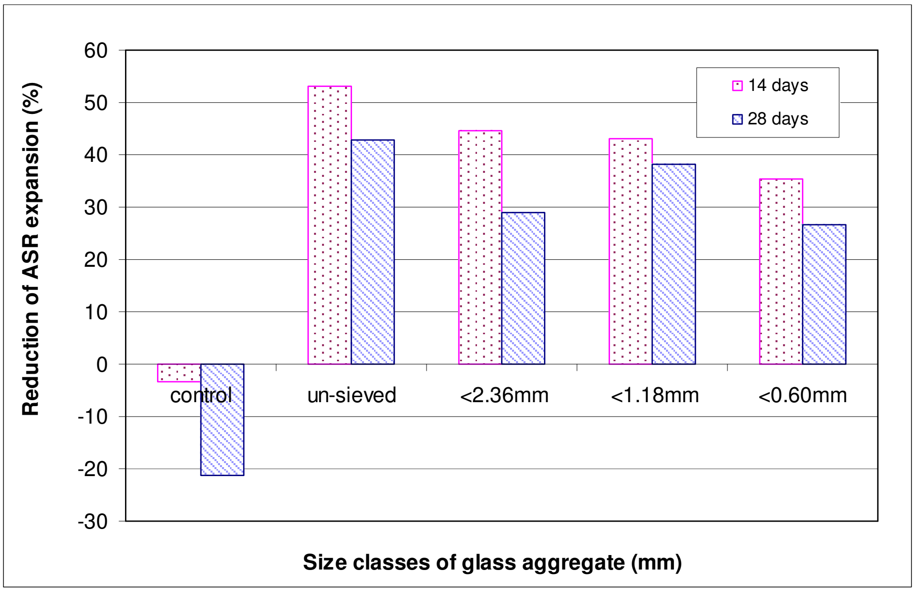


Figure 7.5: Effect of dry-mixed method on the reduction of ASR expansion at 14 and 28 days

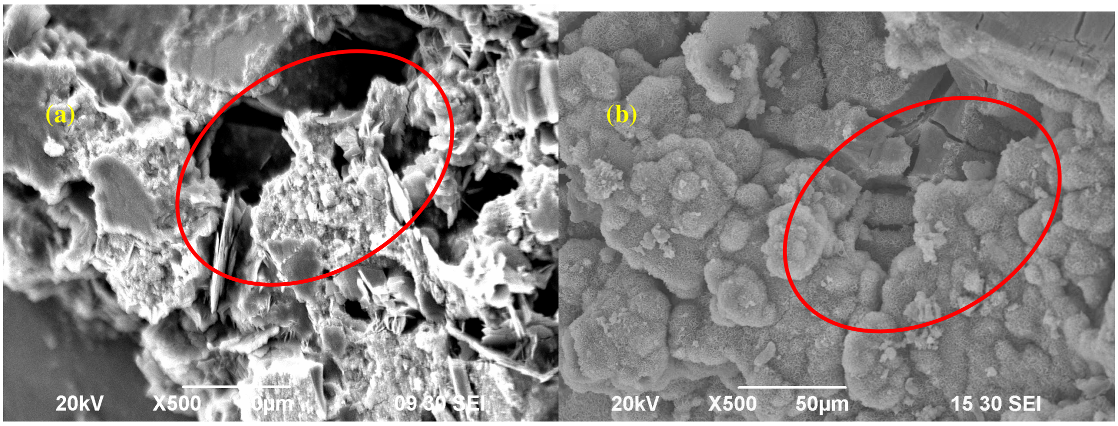


Figure 7.6: SEM image of DM-A (a) before and (b) after exposed to aggressive environment (1 N NaOH at 80°C)

It is known that the ASR expansion is closely related to the durability of concrete. Figure 7.7 shows the effect of wet-mixed and dry-mixed (casting) method on the reduction of flexural strength after the mortar bars were exposed to the aggressive environment (1 N NaOH at 80°C) for 14 days. It is clearly observed that the expansion due to ASR caused a large reduction in the flexural strength especially for the mortar bars prepared with the wet-mixed method. This phenomenon could be due to the increase of ASR gel, resulted in an internal pressure which might eventually lead to expansion and cracking. As seen in Figure 7.8, the mortar bars prepared with using the wet-mixed method irrespective of particle size wet-mixed method experienced severe ASR cracking. From the SEM images, it can be seen that the width of these ASR cracking increase consistently with increasing particle size of glass used while the uses of smaller particle size (less than 600μm or FG-D) had improved the reduction of strength deterioration by about 54.5%.

On the other hand, no cracks were observed in all the mortar bars made by the dry-mixed method. Therefore, the performance of strength deterioration using the dry-mixed method was found to very satisfactory, with an average reduction of 50% in all cases as compared to the wet-mixed method.

Figure 7.7: Effect of wet-mixed and dry-mixed on the reduction of flexural strength after exposed to rapid environment (1 N NaOH at 80°C) for 14 days

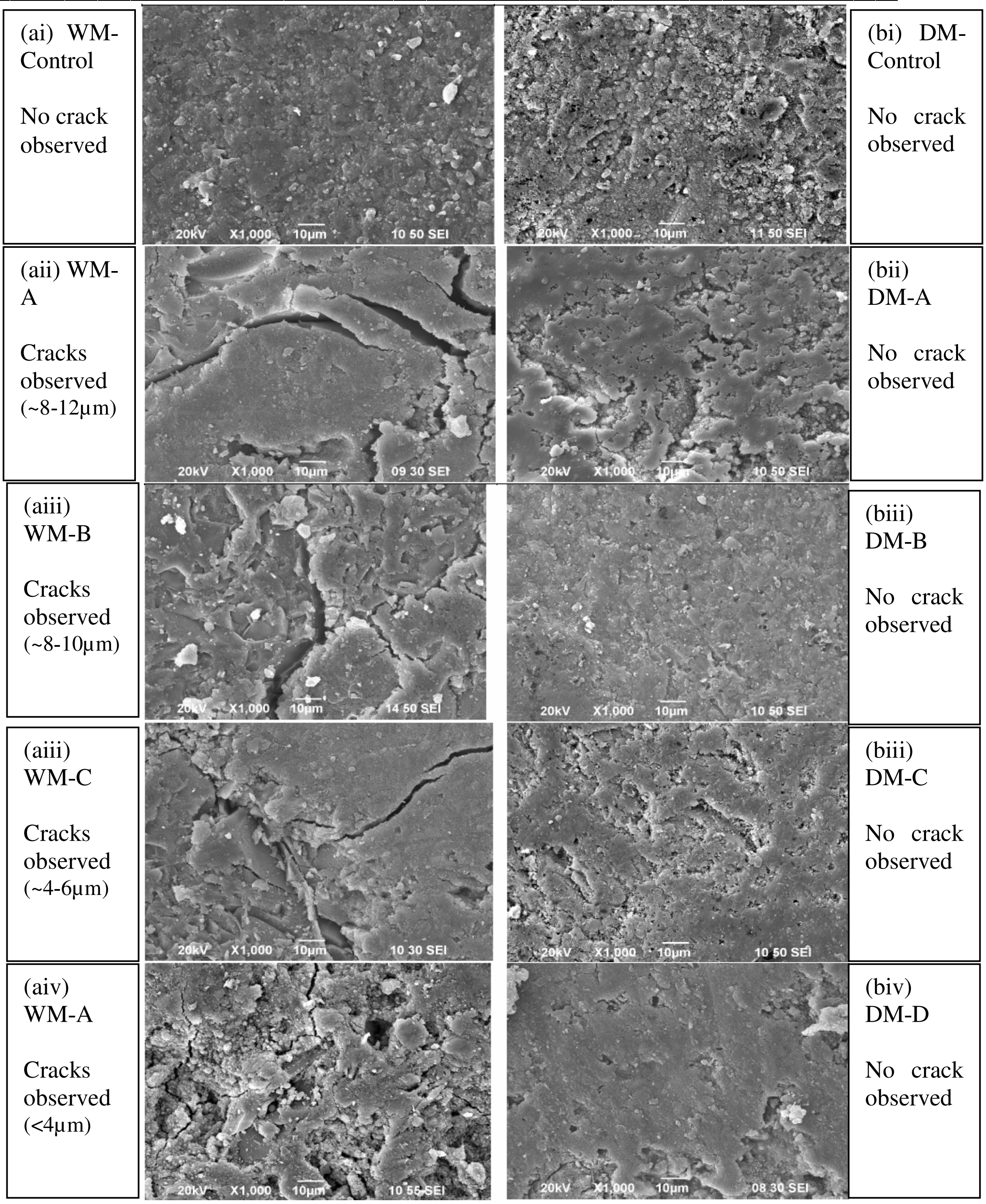


Figure 7.8: SEM image of mortar bars after exposed to rapid environment for 14 days (a) wet-mixed (b) dry-mixed

7.3. Conclusions

The comparison is made between dry-mixed and wet-mixed and the conclusions cab be drawn:

1. The effects of different particle size of FG on the properties of dry-mixed and wet-mixed concrete blocks are similar.
2. With the reduction of particle size of FG (from A-FG to C-FG), the percentages of reduction of compressive strength of wet-mixed concrete were larger than that of dry-mixed concrete. It was because the water and air content that were trapped in the glass particles were believed to be partially squeezed out during the process of fabrication by a large external compressive force on the concrete mixtures for the dry-mixed concrete blocks and led to less reduction of strength.
3. The compressive strength of both dry-mixed and wet-mixed concrete blocks of series-D was higher than that of series-C due to the pozzolanic effect of very fine glass (D-FG) which is beneficial on the compressive strength
4. The effect of water curing on the increase of compressive strength on the wet-mixed concrete was larger than that of the dry-mixed concrete. It was because more capillary pores around the pozzolanic FG particles in wet-mixed concrete which served as a path for water to approach as a necessary component for pozzolanic reaction.
5. Dry-mixed method was very efficient in reducing the ASR expansion especially for larger particle size (highly reactive) glass aggregate. For a given mix proportion, the reduction of expansion was up to about 44% as compared with the wet-mixed method.

The mortar bars made by the dry-mixed method had very small amount of available water and higher porosity, thus, they are able to prevent and accommodate more gel produced due to ASR, resulting lower expansion and cracks.

Chapter 8 – Conclusions and Recommendations

8.1. Conclusions

The conclusions of the study are summarized below:

1. For dry-mixed concrete blocks, a higher W/C ratio was required to achieve the same cohesiveness when the fineness modulus of fine aggregates was reduced.
2. The packing volume ratio reduced as very fine FG was incorporated due to the uniform particle size distributions.
3. The hardened density of the concrete blocks decreased with the increase in the FG because of the lower specific gravity of FG. The replacements of sand by FG increased the water absorption of concrete blocks. The influence of FG content on water absorption was more pronounced when finer FG was used.
4. Inclusion of the very fine FG increased the compressive strength of concrete blocks due to its pozzolanic reactivity. The effect of water curing was more pronounced for concrete blocks made with the finer FG.
5. The replacements of sand by FG increased the water absorption of the wet-mixed concrete blocks. The influence of FG content on water absorption was more pronounced when finer glass was used.
6. The effects of different particle size of FG on the properties of dry-mixed and wet-mixed concrete blocks are similar.
7. Inclusion of FG replacing sand led to the decrease of compressive strength of concrete blocks due to the weak bonding between the glass particles and cement

paste. The percentage of strength reduction of D-series (particle size of FG <600μm) was smaller than C-series (particle size of FG <1.18mm). It was because the pozzolanic reaction of very fine FG was stronger than coarse FG so that it partially compensated the negative effect.

8. With the reduction of particle size of FG (from A-FG to C-FG), the percentages of reduction of compressive strength of wet-mixed concrete were larger than that of dry-mixed concrete. It was because the water and air content that were trapped in the glass particles were believed to be partially squeezed out during the process of fabrication by a large external compressive force on the concrete mixtures for the dry-mixed concrete blocks and led to less reduction of strength.
9. Water curing led to the increase of compressive strength for both dry-mixed and wet-mixed concrete blocks.
10. The compressive strength of both dry-mixed and wet-mixed concrete blocks of series-D was higher than that of series-C due to the pozzolanic effect of very fine glass (D-FG) which is beneficial on the compressive strength
11. The effect of water curing on the increase of compressive strength on the wet-mixed concrete was larger than that of the dry-mixed concrete blocks. It was because more capillary pores around the pozzolanic FG particles in wet-mixed concrete which served as a path for water to approach as a necessary component for pozzolanic reaction.
12. ASR expansion decreased with the reducing particle size of glass, and it became more significant when the particle size of glass used was less than 600 μm.

13. The dry-mixed method was very efficient in reducing the ASR expansion especially for larger particle size (highly reactive) of glass aggregate. For a given mix proportion, the reduction of expansion is up to about 44% as compared with the wet-mixed method. The mortar bars made by the dry-mixed method had very small amount of available water and higher porosity, thus, they were able to prevent and accommodate more gel produced due to ASR, resulting in lower expansion and cracks.
14. Both PFA and MK can effectively mitigate ASR expansion regardless of the particle size of glass used. The reduction of ASR expansion of mortar bars containing PFA was clearly more effective than MK in the case of 5%. However, at higher content at 20%, both PFA and MK showed similar effectiveness in suppressing ASR expansion.

8.2. Recommendations

The recommendations of concrete blocks mixing and further research works are listed as follow:

1. Based on the experimental results, it is good to use a higher amount of fine glass with particle size smaller than 600μm to produce concrete blocks. It is because it contributes to higher strength (or smaller reduction of strength) and higher ASR resistance when compared with using glass with larger particle size of fine glass.
2. The experiment could be conducted further by using waste glass with a single uniform color instead of mixed color because waste glass with different colors may

influence the ASR resistance of concrete. For instance, chromium oxide in green glass is defined as an ASR suppressant. (Meyer et al., 1996)

3. It is worth conducting the study with a longer period curing to study how the strength of the concrete blocks change with different particle size of waste glass used due to the effect of ASR. This provides an important data for reference of using waste glass as aggregate in industrial implication.
4. The effect of water-cement (W/C) ratio to the reactivity of pozzolanic reaction of fine glass is worth to study which the relationship between W/C ratio and increment of strength of concrete containing fine glass can be found.

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Appendix - List of Publications

1) Lee G, Wong YL, Poon CS, Mechanical Properties of Pre-cast Dry-mixed Concrete Paving Block Incorporating with Different Particle Size of Waste Glass Cullet Replacing River Sand, The 11th International Summer Symposium, Japan Society of Civil Engineers, September, 2009.

2) Lee G, Poon CS, Wong YL, Ling TC, Effects of Recycled Fine Glass Aggregates on the Properties of Dry-Mixed Concrete Blocks, submitted to Construction and Building Materials for possible publication, 2010.

3) Lee G, Ling TC, Wong YL, Poon CS, Effects of Crushed Glass Cullet Sizes, Casting Methods and Pozzolanic Materials on ASR of Concrete Blocks, Construction and Building Materials 2011; 25: 2611-8.