# Feasibility Study on Use of Supplementary Cementitious Materials to Mitigate Alkali-silica Reaction in Concrete Made with Volcanic Aggregates

**GEO Report No. 354**

**H.D. Wong & W.S.M. Tam**

**Geotechnical Engineering Office**
**Civil Engineering and Development Department**
**The Government of the Hong Kong**
**Special Administrative Region**

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# Preface

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet.

Raymond WM Cheung
Head, Geotechnical Engineering Office
March 2022

# Foreword

With the support of the Standing Committee on Concrete Technology (SCCT), the Public Works Central Laboratory (PWCL) carried out a feasibility study on the use of supplementary cementitious materials, including GGBS, PFA, and CSF to mitigate alkali-silica reaction (ASR) in concrete with volcanic aggregates.

This Technical Note presents the findings of the study based on a two-year laboratory investigation on the length measurements of the expansion of the concrete prisms.

Mr. H.D. Wong undertook the study in conjunction with the study team members under my supervision. Messrs. Ryan C.Y. Chi, Martin C.K. Wong and Wallace S.M. Tam organized and supervised the laboratory work with the assistance of Messrs. Andy Tam, W.C. Leung, K.L. Wong, and Ms. M.T. Lai of the PWCL. Expert advices were provided by Mr. Peter W.C. Leung, Professors Albert Kwan of the University of Hong Kong, Y.L. Wong of the Hong Kong Polytechnic University, Deng Min (鄧敏) and Lu Duyou (盧都友) of the Nanjing University of Technology, Dr. Jan Lindgård of RILEM Technical Committee-AAA (2014-2019), and members of the SCCT and the Hong Kong Concrete Institute. The Ready Mixed Concrete Committee of the Hong Kong Construction Materials Association provided technical and laboratory support to the study. All contributions are gratefully acknowledged.

T.K.C. Wong
Chief Geotechnical Engineer/Standards and Testing

# Abstract

Volcanic aggregates are rarely used in concrete production for public works projects in Hong Kong. The main reason is the risk of deleterious expansion due to alkali-silica reaction (ASR) in concrete.

Overseas studies have shown that the expansion due to alkali-silica reaction can be mitigated by using certain supplementary cementitious materials, such as ground granulated blastfurnace slag (GGBS), pulverized fly ash (PFA), and condensed silica fume (CSF). In the construction of a tall commercial building in Hong Kong, volcanic aggregates combined with PFA and CSF had been used in the construction of the mega central concrete cores.

The PWCL carried out an in-house study on the feasibility of using GGBS, PFA and CSF to mitigate the deleterious effects of ASR on concrete made with local volcanic aggregates from the Anderson Road Quarry and the Lam Tei Quarry. The laboratory investigation commenced in late 2014.

The study finds out that, by replacing the cement with adequate amount of GGBS, PFA and CSF, the 2-year expansion of the concrete prism due to the presence of ASR can be controlled within 0.02%, which is well below the 0.05% limit as stated in CS1:2010.

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# 1 Introduction

In Hong Kong's public works projects, volcanic rocks are generally not allowed in concrete production due to the risk of concrete deterioration caused by alkali-silica reaction (ASR). However, overseas studies have shown that volcanic rocks can be used in the concrete production provided that the effects of ASR are suitably controlled.

Tunnelling projects in the territory usually generate huge amount of surplus rocks, which may be volcanic in nature or blended with granites. In addition, cavern developments may generate a large quantity of volcanic rocks. These rocks are in fact valuable resources to local construction industry if they can be used properly in concrete production.

Supported by the Standing Committee on Concrete Technology (SCCT) and the Hong Kong Concrete Institute (HKCI), the Public Works Central Laboratory (PWCL) carried out an in-house feasibility study on use of supplementary cementitious materials to mitigate the deleterious effects of ASR in concrete made with local volcanic aggregates, which are obtained from both the Anderson Road Quarry and the Lam Tei Quarry[1]. The study commenced in late 2014.

# 2 Literature Review

## 2.1 Alkali-silica Reaction in Concrete

ASR is a chemical reaction between the alkaline pore solution and reactive silica in certain types of aggregates, such as volcanic tuff aggregates. The reaction leads to the formation of a gel-like product. In the presence of water moisture, the gel-like product will expand and damage the concrete.

In 1991, the first case of deterioration in concrete caused by ASR in Hong Kong was found on a water retaining structure in a sewage treatment plant constructed in 1981. The ASR process is very slow and usually takes around 10 years or more after construction for the cracks to be visible. In some extreme cases, the cracks may appear within a few years after construction (Leung et al, 1995). However, the ASR process may also be affected by external factors. According to the Technical Guidance on appraisal of structural effects of ASR by the Institution of Structural Engineer (IStructE) (1992), there is no time limit for expansion to occur in concrete containing sufficient reactive silica and internal/external alkalis, such as industrial chemicals. For concrete made of certain volcanic aggregates, such as rhyolite and andesite, the expansion may continue for more than 30 to 60 years. Rhyolite and andesite are common types of volcanic rocks found in areas such as Lantau Island and Tuen Mun (Li, 2007).

The visual features of structures affected by ASR are typically map patterned cracks, cracks parallel to the main reinforcements, pop-outs or swelling of concrete, etc. Some typical pattern of the cracks caused by ASR are shown in Figure 2.1. It is however important to note that it will be very difficult to cease the ASR once started.

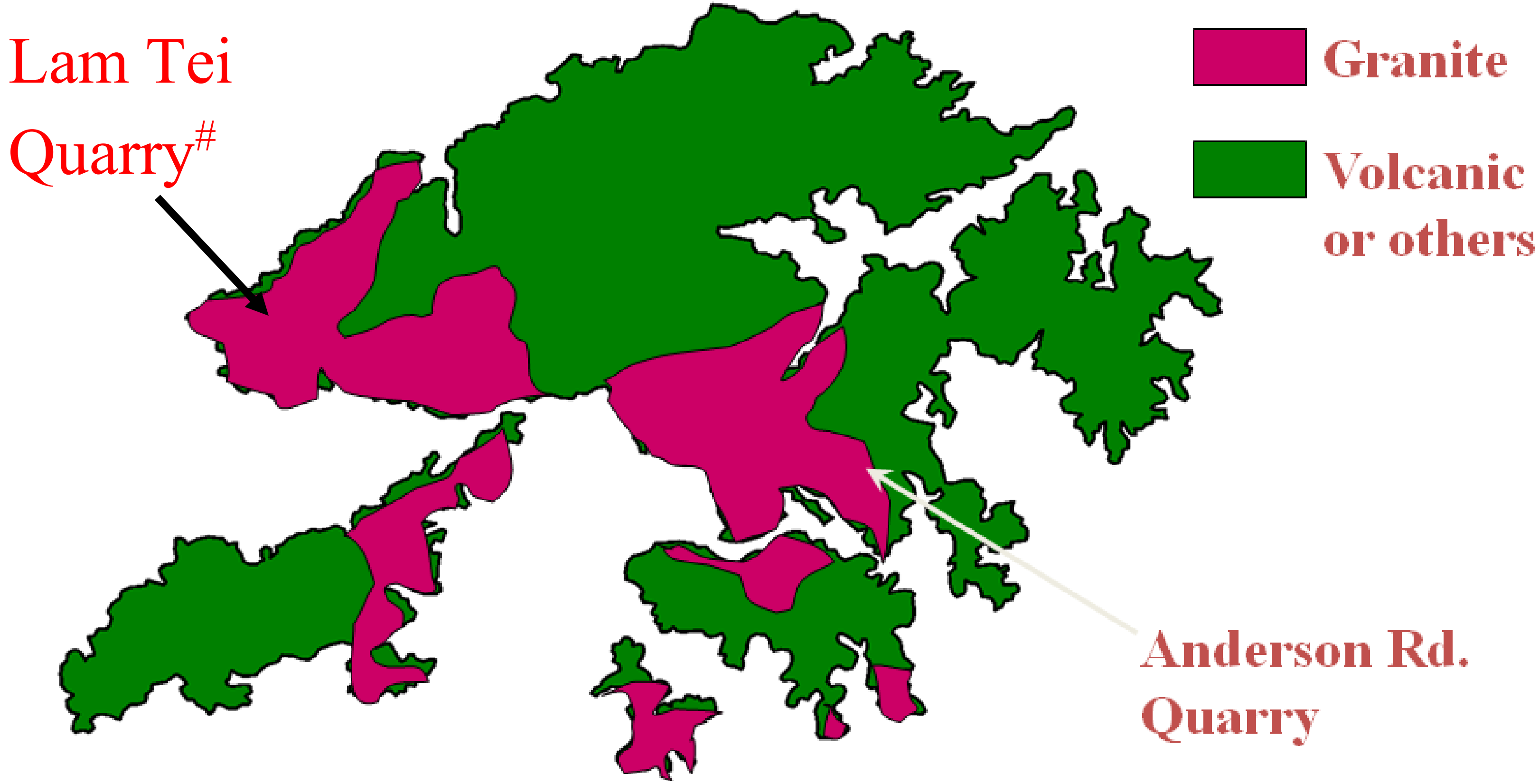
[1] The volcanic aggregates (mainly volcanic tuff) in Lam Tei Quarry used in this study were produced by crushing the volcanic rocks originated from the XRL project of MTR Contract 822 – Tse Uk Tsuen Shek Yam Tunnels.


**Figure 2.1 Typical Pattern of ASR Cracks**

## 2.2 Aggregate Supply and Use of Volcanic Aggregates in Concrete

Figure 2.2 is a simplified rock map showing a rough distribution of granite rock and volcanic rock in Hong Kong, which indicates that more than half of the land area are volcanic or non-granitic rocks. Volcanic rocks, like volcanic tuff, are strong and of high E-modulus. The local tunnel projects or cavern developments are most likely to generate large amount of reactive volcanic rocks. The volcanic tuff will be a useful local resource if they can be used in concrete production. A recent study by the Hong Kong University of Science and Technology also found that volcanic aggregates can be used for production of concrete with compressive strength over 102 MPa and E-modulus over 39.5 GPa, which is ideal for tall building construction (Li et al, 2016). In fact, volcanic tuff from the Anderson Road Quarry was used, combined with PFA (35%) and CSF (5%), for the construction of mega central concrete cores of a tall commercial building in Hong Kong. However, reactive volcanic tuff aggregates have not been extensively used in Hong Kong's concrete production because of the potential ASR problems.

Section 16 – Concrete and Joints in Concrete of the General Specification for Civil Engineering Works specifies that aggregates in the alkali "Reactive" category with expansion exceeding 0.2% determined in accordance with Section 22 of CS1:2010 shall not be used. Such "no ASR-reactive aggregate" requirement can be maintained so far mainly due to two favourable conditions: (i) there are still sufficient and stable supply of non-ASR-reactive aggregates at reasonable cost from quarries in Guangdong Province, and (ii) the relatively low cost of the aggregates for concrete production as compared with the total cost of the construction project. The question is how long such favourable conditions will last. Currently, over 90% of the aggregates for ready mixed concrete production in Hong Kong were supplied by five quarries in Guangdong Province, among which four quarries are of small size. Due to the ever tightening up of the environmental policy in Guangdong Province, the production lives of small quarries in the region are becoming very short, around 10 years. New quarries may be located in the north-west borderland of Guangdong and even in more remote provinces such as Guangxi. As a result, the cost of aggregates may go up.




Note (#): The volcanic aggregates (mainly volcanic tuff) in Lam Tei Quarry used in this study were produced by crushing the volcanic rocks originated from the XRL project of MTR Contract 822 – Tse Uk Tsuen Shek Yam Tunnels.

**Figure 2.2 Simplified Rock Map in Hong Kong**

## 2.3 Prevention of ASR – Overseas Experience and Practice

The commonly adopted methods of preventing ASR in concrete structures include:

(i) lowering the alkali content in cement;

(ii) adding of lithium compounds; and

(iii) adding of supplementary cementitious materials.

Lowering the alkali content in cement (i.e. alkali content less than 0.6% $Na_2Oeq$) is effective in ASR prevention but only to some extent. In accordance with GEO Report No. 167 - "The 2004 Review on Prevention of Alkali Silica Reaction in Concrete", the alkali content in concrete using reactive aggregates should be limited to 3.0 $kg/m^3$ for Class 1 Structures[2] or for Class 2 Structures[3] using potentially reactive aggregates (Chak et al, 2008). However, to guarantee the limit of alkali content in cement or in concrete is not easy and will increase the cost of cement or concrete production. Moreover, the risk of future alkali intrusion from the environment cannot be completely eliminated.

Lithium compounds are effective in preventing ASR damage in concrete structures. However, there is very limited information on its field applications as well as long term performance.

A practical and economical means of mitigating ASR damage is using pozzolanic materials (or supplementary cementitious materials) such as pulverised fly ash (PFA), ground granulated blastfurnace slag (GGBS) and condensed silica fume (CSF) (Roty et al, 1996). Roty's study also found that replacing Portland cement by 30% Class F fly ash can effectively mitigate the ASR expansion. Another study reported that a minimum replacement level of 50% GGBS or 25% fly ash was effective in mitigating the ASR expansion (Touma et al, 2001). A hydropower structure in Ontario, Canada was constructed with the use of 50% GGBS cement and ASR-reactive aggregates. The concrete structure still performed well 10 years after construction (Rogers et al, 2000). Other researches recommended to include 25% - 40% low calcium fly ash, or 40% - 50% GGBS for the mitigation of ASR in concrete (Malvar et al, 2001). Researchers in Canada found that the concrete structures made with reactive aggregates and a replacement of cement with 50% GGBS were still in excellent condition 15 years after construction (Hooton et al, 2000). A study by Hogan & Meusel (1981) reported that a replacement of 40% - 65% GGBS of the total cementitious material was able to virtually eliminate the effects of ASR. The resistance to ASR provided by GGBS was mainly due to the reduction of (1) concrete permeability, (2) amount of alkali in the concrete, and (3) amount of CaOH for ASR (ACI 233R-95, 2000).

According to the Slag Cement Association (SCA), the replacement level of GGBS for ASR control was typically in the range between 30% and 60% by mass of total cementitious

[2] Class 1 Structures means some deterioration from ASR is acceptable e.g., temporary or short service life structures, easily replaceable elements.

[3] Class 2 Structures means minor ASR and resulting cosmetic cracking is acceptable e.g., most building and civil engineering structures, which design life is in the regime of tens to a hundred or so years.

materials (Figure 2.3). The effects of slag on the expansion of concrete containing reactive aggregate by a 2-year concrete prism test study are shown below.

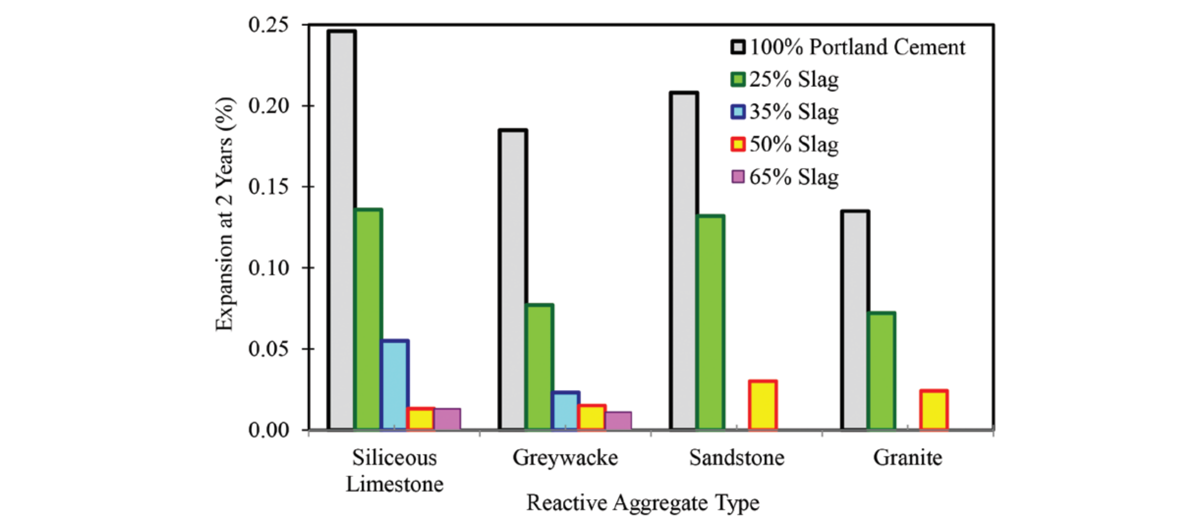



**Figure 2.3 Effects of Percentage of Slag on ASR Control for Different Types of Aggregate (SCA, 2013)**

According to CUR[4] Recommendation 38 – Dutch Guideline on ASR-prevention, if the cement is replaced by a minimum of 25% fly ash, or 50% GGBS, then the potential reactivity of the aggregates is of no concern (Heijnen & Larbi, 1999). There were several cases of ASR damage on old (> 25 years) bridges, locks, and viaducts in the Netherlands. However, Heijnen & Larbi (1999) said that no case was reported of a structure in which the concrete was made with blended cement containing high GGBS content (≥ 50%). In CUR Recommendation 89, which applies to concrete according to EN 206-1, for ASR-reactive aggregates, either cement type CEM II/B-V (PFA content ≥ 25% or 30%) or CEM III/A (GGBS content ≥ 50%) or CEM III/B (GGBS content ≥ 66%) should be used for ASR prevention (CURNET, 2008).

The Standing Committee on Concrete Technology conducted a study on the use of volcanic tuff aggregates from Anderson Road Quarry in concrete in 2004. The study recommended that (i) with the inclusion of at least 25% PFA, volcanic tuff aggregates from the quarry could be used in concrete, and (ii) volcanic tuff aggregates should not be used in concrete that would be exposed to aggressive marine conditions.

## 3 Study Objectives and Methodology

### 3.1 Study Objectives

The study objectives are as follows:

(1) To find out potential concrete design mix(es) containing

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[4] CUR stands for Centre for Civil Engineering Research and Codes.

supplementary cementitious materials (SCM) (such as GGBS, PFA, and CFS) to mitigate the deleterious ASR expansion in concrete made of local volcanic tuff; and

(2) To investigate the correlation between laboratory results and field measurements in the long term[5].

### 3.2 Methodology

The study is based on the concrete prism test to determine the alkali-silica reaction potential of concrete made with volcanic aggregates and various combinations of SCM, like GGBS, PFA, and CFS. As a control, two sources of volcanic aggregates are selected from Lam Tei Quarry and Anderson Road Quarry. For each mix combination, three concrete prism specimens were made out of each batch of concrete in accordance with Section 11 of CS1:2010. The expansion measurement of each concrete prism specimen was carried out in accordance with CS1:2010, Section 23 – Determination of Alkali Silica Reaction Potential by Concrete Prism Test.

## 4 Description of Test Materials

The physical and chemical properties of the cement, GGBS, PFA and CSF used in the study are given in Tables 4.1 to 4.6.

The volcanic aggregates obtained from both the Anderson Road Quarry and the Lam Tei Quarry are mainly volcanic tuff. Due to limited availability of aggregates, tests on their physical and chemical properties were not carried out.

**Table 4.1 Physical Properties of Cement (Brand: Norcem)**

| Test | Unit | BS EN 197-1:2000 Strength Class 52.5N Requirement | Test Results |
|---|---|---|---|
| Density | $kg/m^3$ | Not Specified | --- |
| Fineness (specific surface) | $cm^2/g$ | Not Specified | 5940 |
| Standard consistence | % | Not Specified | 33.1 |
| Initial setting time | min | ≥ 45 | 115 |
| Soundness | mm | ≤ 10 | 0.0 |
| Compressive strength (2 days) | MPa | ≥ 20 | 40.4 |
| Compressive strength (28 days) | MPa | ≥ 52.5 | 57.9 |

[5] This report presents study results up to 2 years. The field measurements are still continuing.

**Table 4.2 Chemical Properties of Cement (Brand: Norcem)**

| Test | Unit | BS EN 197-1:2000 Strength Class 52.5N Requirement | Test Results |
|---|---|---|---|
| Potassium oxide content ($K_2O$) | % | Not Specified | 1.07 |
| Sodium oxide content ($Na_2O$) | % | Not Specified | 0.50 |
| Sulphate content (as $SO_3$) | % | ≤ 4.0 | 3.60 |
| Insoluble residue | % | ≤ 5.0 | --- |
| Loss on ignition | % | ≤ 5.0 | 2.90 |
| Chlorine content | % | ≤ 0.10 | 0.06 |
| Total alkali (equivalent $Na_2O$) | % | Not Specified | 1.20 |

**Table 4.3 Physical and Chemical Properties of GGBS**

| Test | Unit | BS EN 15167-1:2006 Requirement | Test Results |
|---|---|---|---|
| Physical Properties | | | |
| Density | $kg/m^3$ | Not specified | 2850 |
| Fineness (specific surface) | $m^2/kg$ | ≥ 275 | 499 |
| Standard consistence | % | Not specified | 30.5 |
| Initial setting time | min | ≤ twice of initial setting time for Portland cement used [i.e. 280] | 210 |
| Activity Index (7 days) | % | ≥ 45 | 66 |
| Activity Index (28 days) | % | ≥ 70 | 89 |
| Chemical Properties | | | |
| Loss on ignition, corrected for oxidation of sulphide | % | ≤ 3.0 | 1.9 |
| Sulphate ($SO_3$) | % | ≤ 2.5 | 0.2 |
| Chloride | % | ≤ 0.10 | 0.02 |
| Magnesium oxide (MgO) | % | ≤ 18 | 10.4 |
| Moisture content | % | < 1.0 | 0.5 |

**Table 4.4 Physical and Chemical Properties of PFA**

| Test | Unit | BS 3892-1:1997 Requirement | Test Results |
|---|---|---|---|
| Physical Properties | | | |
| Particle Density | $kg/m^3$ | ≥ 2000 | 2270 |
| Fineness | % | ≤ 12.0 | Max. 8.2 |
| Standard consistence | % | Not specified | 28 |
| Initial setting time | min | ≥ initial setting time of Portland cement used | 185 |
| Soundness | mm | ≤ 10 | 1.0 |
| Chemical Properties | | | |
| Loss on ignition | % | ≤ 7 | Max. 3.64 |
| Sulphate content ($SO_3$) | % | ≤ 2 | 0.4 |
| Chloride ion content | % | ≤ 0.10 | 0.05 |
| Calcium oxide content (CaO) | % | ≤ 10.0 | 3.2 |
| Sodium oxide content ($Na_2O$) | % | Not specified | Max. 1.00 |
| Potassium oxide content ($K_2O$) | % | Not specified | Max. 1.62 |
| Moisture content | % | ≤ 0.5 | Max. 0.1 |

**Table 4.5 Physical and Chemical Properties of CSF**

| Test | Unit | CAN/CSA-A23.5-M86 Requirement | Test Results |
|---|---|---|---|
| Physical Properties | | | |
| Moisture content | % | ≤ 3.0 | 0.91 |
| Fineness | % | ≤ 10 | 0.8 |
| Density | $g/cm^3$ | Not specified | 2.21 |
| Accelerated Pozzolanic Activity Index with OPC at 7 days min. % of control | % | ≥ 85 | 101 |
| Soundness | % | < 0.2 | 0* |
| Chemical Properties | | | |
| Sulphur trioxide ($SO_3$) | % | ≤ 2.0 | 0.45 |
| Silicon Dioxide ($SiO_2$) | % | ≥ 85 | 93.1 |
| Loss on ignition | % | ≤ 6.0 | 2.11 |

Note: Tests were carried out in accordance with CAN/CSA-A23.5-M86 (Canadian Standard).

*The soundness of the CSF was determined in accordance with BS 4550 instead of ASTM C311 with test result of 0 mm.

**Table 4.6 Mix Proportions of Concrete Prisms**

| Mix No. | Cement (Norcem) Replacement Level |
|---|---|
| Mix 1 | 0% (cement only) |
| Mix 2 | 35% PFA |
| Mix 3 | 35% PFA + 5% CSF |
| Mix 4 | 50% GGBS |
| Mix 5 | 70% GGBS |
| Mix 6 | 50% GGBS + 5% CSF |

# 5 Laboratory Investigation

## 5.1 Concrete Mix Design

The concrete mixes for the study comprised a Norcem[6] concrete and five SCM concrete mixes for each of the two aggregate sources from the Lam Tei Quarry and the Anderson Road Quarry. The designed mix combinations and related mix IDs for each of the volcanic aggregates sources are shown in Tables 5.1 and 5.2. Details of the concrete mixes for the Anderson Road Quarry and the Lam Tei Quarry were shown in Tables 5.3 and 5.4 respectively.

**Table 5.1 Designed Mix Combinations**

| Cementitious Material | Cement Replacement Level | | | |
|---|---|---|---|---|
| | Control | 35% | 50% | 70% |
| 100% Norcem | ✔ | | | |
| PFA | | ✔ | | |
| PFA + 5% CSF[(1)] | | ✔ | | |
| GGBS | | | ✔ | ✔ |
| GGBS + 5% CSF[(1)] | | | ✔ | |

Note: [(1)] 5% CSF refers the percent by weight in the concrete mix.

**Table 5.2 Mix IDs**

| % of Total Cementitious Materials | Mix ID | |
|---|---|---|
| | Anderson Road Quarry | Lam Tei Quarry |
| 100% Norcem | MA0 | ML0 |
| 35% PFA | MA1 | ML1 |
| 35% PFA + 5% CSF[(1)] | MA2 | ML2 |
| 50% GGBS | MA3 | ML3 |
| 70% GGBS | MA4 | ML4 |
| 50% GGBS + 5% CSF[(1)] | MA5 | ML5 |

Note: [(1)] 5% CSF refers the percent by weight in the concrete mix.

[6] Norcem is a type of reference cement (with known total alkali content of range 0.9% - 1.2% sodium oxide equivalent) from Norcem A.S. R&D Department, 3950 Brevik, Norway.

**Table 5.3 Mix Proportions of Concrete for Anderson Road Quarry**

1 Metre Proportions (1 $m^3$)

| Mix ID | Cement (kg) | PFA / GGBS (kg) | CSF (kg) | 20 mm Agg (kg) | 10 mm Agg (kg) | Rock Fines (kg) | Water (kg) | C330 (L) | Later Dosage C330 (L) | Density ($kg/m^3$) | Free Water/ Binding material Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| MA0 | 500 | 0 | 0 | 580 | 230 | 870 | 180 | 7.50 | 5.00 | 2373 | 0.380 |
| MA1 | 325 | 175 | 0 | 570 | 220 | 860 | 182 | 7.00 | 2.50 | 2342 | 0.379 |
| MA2 | 300 | 175 | 25 | 570 | 220 | 850 | 182 | 7.50 | 2.50 | 2333 | 0.380 |
| MA3 | 250 | 250 | 0 | 580 | 230 | 865 | 183 | 6.50 | 2.00 | 2367 | 0.380 |
| MA4 | 150 | 350 | 0 | 580 | 225 | 870 | 183 | 7.00 | 2.00 | 2368 | 0.380 |
| MA5 | 225 | 250 | 25 | 570 | 220 | 875 | 183 | 7.50 | 1.50 | 2358 | 0.380 |

**Table 5.4 Mix Proportions of Concrete for Lam Tei Quarry**

| Mix ID | Cement (kg) | PFA / GGBS (kg) | CSF (kg) | 20 mm Agg. (kg) | 10 mm Agg. (kg) | Rock Fines (kg) | Water (kg) | C330 (L) | Later Dosage C330 (L) | Density (kg/m$^3$) | Free Water/ Binding material Ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ML0 | 500 | 0 | 0 | 585 | 225 | 870 | 182 | 6.50 | 3.00 | 2372 | 0.379 |
| ML1 | 325 | 175 | 0 | 570 | 225 | 865 | 183 | 6.00 | 2.00 | 2352 | 0.379 |
| MA2 | 300 | 175 | 25 | 570 | 225 | 850 | 183 | 6.50 | 2.00 | 2337 | 0.380 |
| ML3 | 250 | 250 | 0 | 575 | 225 | 875 | 183 | 5.50 | 2.00 | 2366 | 0.378 |
| ML4 | 150 | 350 | 0 | 570 | 220 | 880 | 183 | 6.00 | 2.00 | 2362 | 0.379 |
| ML5 | 225 | 250 | 25 | 565 | 215 | 885 | 183 | 6.50 | 2.00 | 2357 | 0.380 |

## 5.2 Test Methods/Procedures

For each source of aggregate, two batches of concrete were prepared. Three concrete prism specimens (size: 75 mm x 75 mm x 250 mm) were made out of each batch of concrete in accordance with Section 11 of CS1:2010. The expansion measurements of concrete prism specimens were carried out in accordance with CS1:2010, Section 23 – Determination of Alkali Silica Reaction Potential by Concrete Prism Test.

The zero measurement (length, $L_o$ and weight, $W_o$) of the specimens were taken 24 hours after demoulding, with each prism removed from its polythene bag, but leave the wrapping and rubber bands undisturbed. On the 7$^{th}$ day from the mixing, another measurement was carried out for the specimens. Further measurements (length, $L_t$ and weight, $W_t$) of the specimens were carried out at the end of periods 2, 4, 13, 26, and 52 weeks after mixing.

In the 2$^{nd}$ year, measurements (length, $L_t$ and weight, $W_t$) of the specimens were carried out at the end of periods 65, 78, 91 and 104 weeks for SCM mixes.

Each increase as a percentage of the zero measurement (Expansion, $E_t$ and weight change, $M_t$) was calculated by:

$$E_t\,(\%) = 100 \text{ x } (L_t - L_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.1)$$

$$M_t(\%) = 100 \text{ x } (W_t - W_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.2)$$

In addition, the average expansion and weight change of the three specimens for each batch was calculated.

## 5.3 Storage and Test Environment

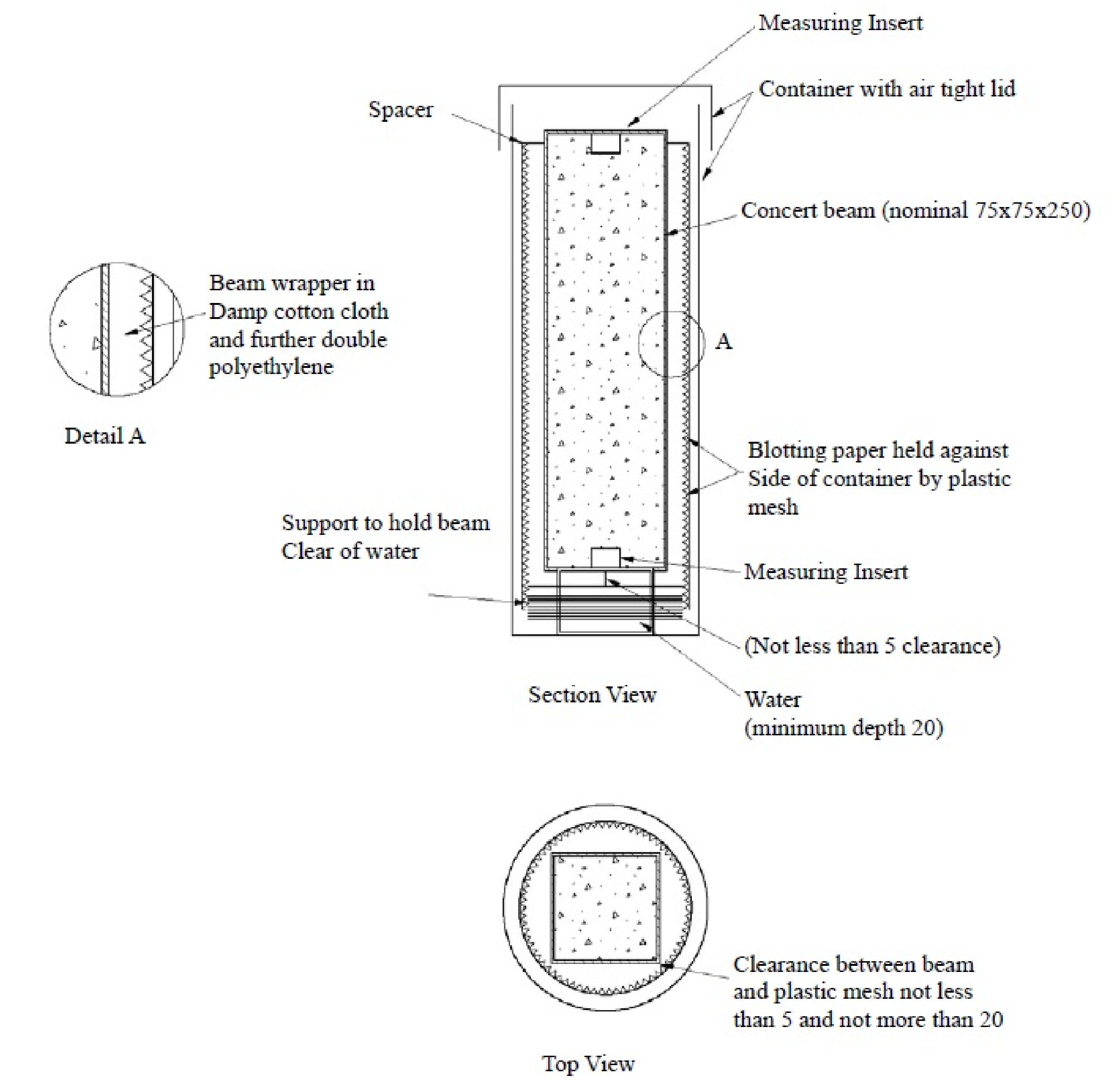
### 5.3.1 Before Zero Measurement

After demoulding, the prisms were wrapped in wet cloth and polythene bags and stored for 24 hours at 20±2ºC until the zero or initial measurement.

### 5.3.2 Before Subsequent Measurements

After the initial measurement, each prism was wrapped with twill weave cotton (saturated with distilled water). The wrapped prism was placed into a polythene lay-flat tubing of the same length as the prism. The whole pack was placed in polythene bag with 5 ml of distilled water pouring over the upper end face of the prism before sealing the bag. The bagged prism was then placed in a stainless steel storage container, in which there was at least 20 mm depth of distilled water. For details, please refer to Figure 5.1.

The stainless steel storage container was then placed in a humidity chamber with temperature kept at 38±2ºC.




Note: All dimensions are in mm.

**Figure 5.1 Container to Provide Humid Environment around Concrete Prism**

## 5.4 Test Results

The test results of expansion and weight changes of the concrete prism test are shown in Tables 5.5 to 5.16 and Figures 5.2 to 5.5.

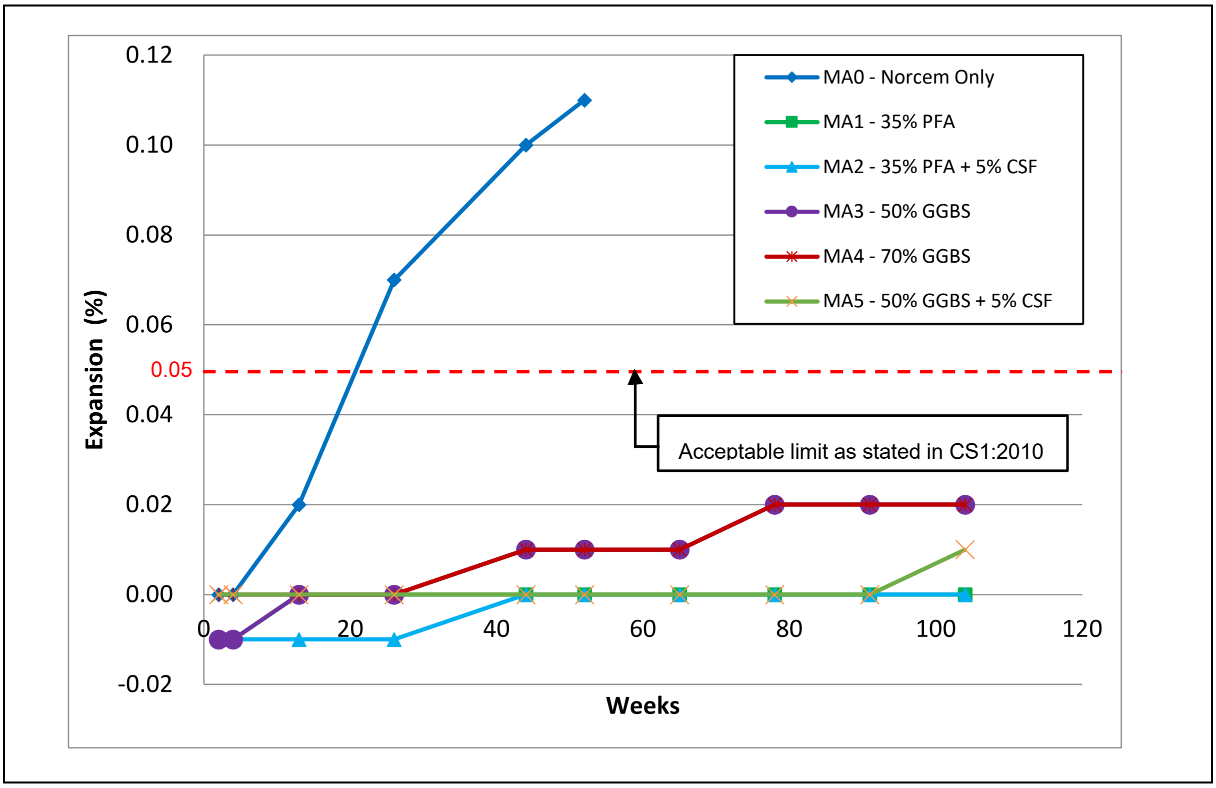



**Figure 5.2 Average Expansion of Concrete Prisms (Anderson Road Quarry)**

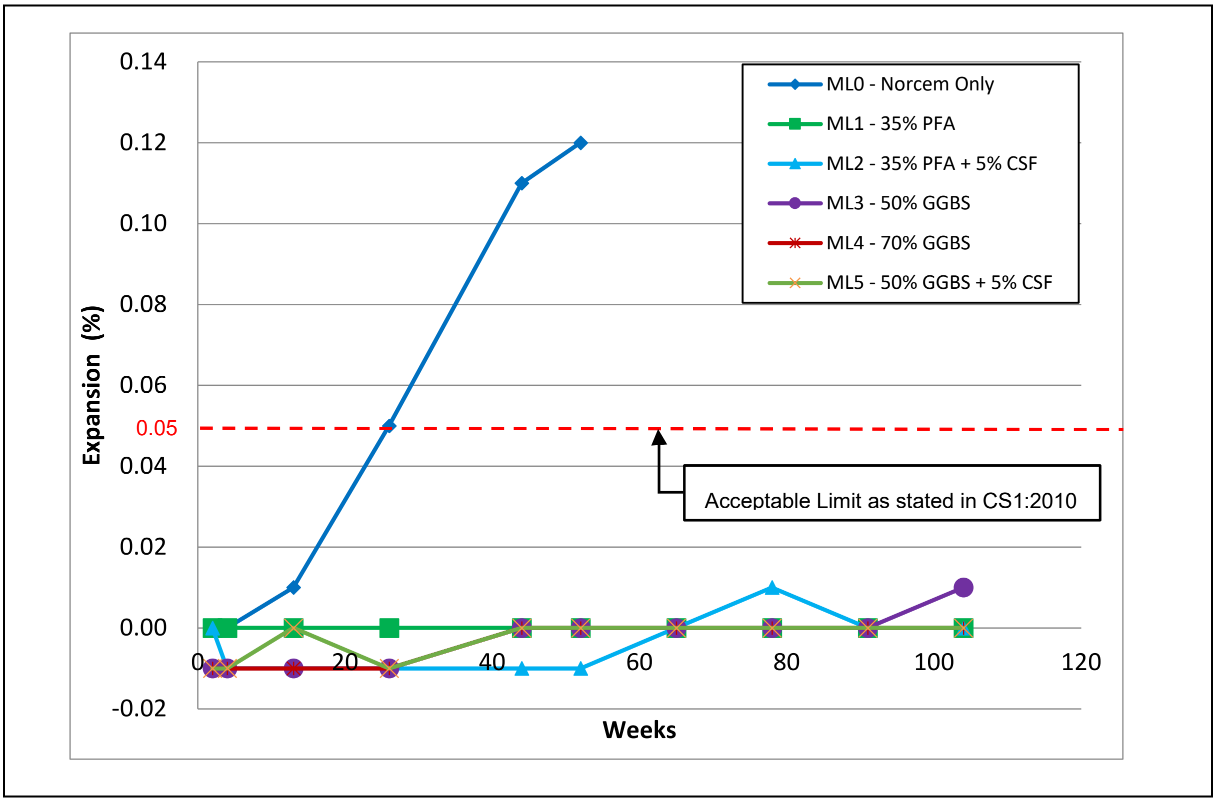



**Figure 5.3 Average Expansion of Concrete Prisms (Lam Tei Quarry)**

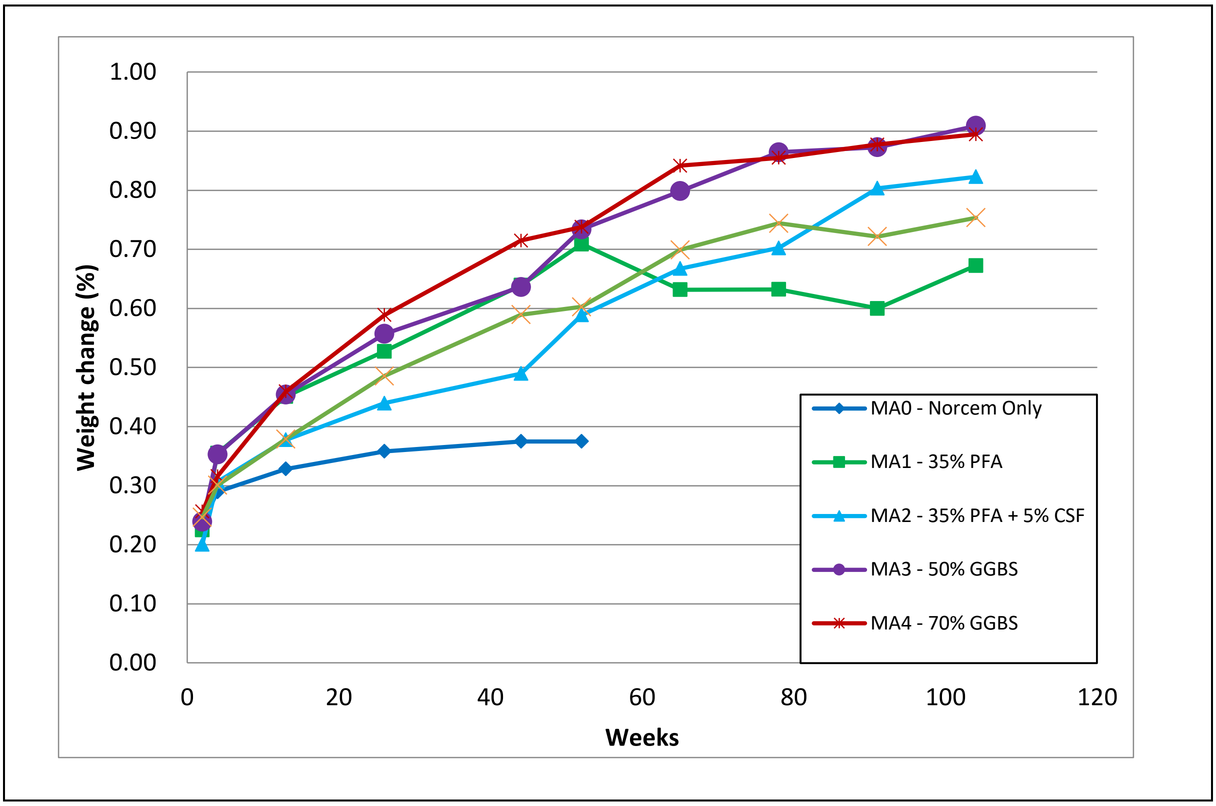



**Figure 5.4 Weight Change of Concrete Prisms (Anderson Road Quarry)**

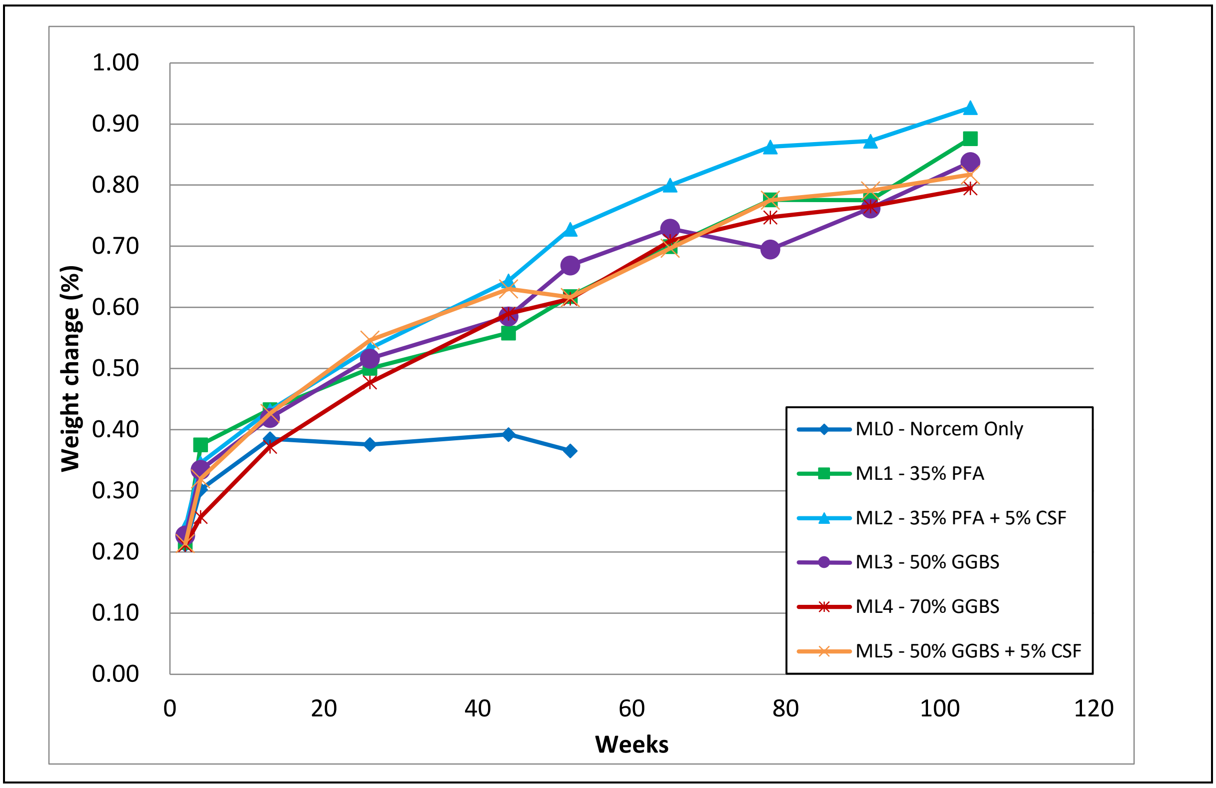



**Figure 5.5 Weight Change of Concrete Prisms (Lam Tei Quarry)**

**Table 5.5 Test Results of Expansion and Weight Change of the Concrete Prism (Lam Tei Quarry, 100% Norcem)**

| ML0 | Mix 1 - 100% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | 0.00 | 0.00 | 0.01 | 0.05 | 0.11 | 0.12 | - | - | - | - |
| Weight change (%) | 0.21 | 0.30 | 0.39 | 0.38 | 0.39 | 0.37 | - | - | - | - |

**Table 5.6 Test Results of Expansion and Weight Change of the Concrete Prism (Lam Tei Quarry, 35% PFA)**

| ML1 | Mix 2 - 35% PFA + 65% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Weight change (%) | 0.22 | 0.38 | 0.43 | 0.50 | 0.56 | 0.62 | 0.70 | 0.78 | 0.78 | 0.88 |

**Table 5.7 Test Results of Expansion and Weight Change of the Concrete Prism (Lam Tei Quarry, 35% PFA + 5% CSF)**

| ML2 | Mix 3 - 35% PFA + 5% CSF + 60% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | 0.00 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | 0.00 | 0.01 | 0.00 | 0.00 |
| Weight change (%) | 0.24 | 0.35 | 0.43 | 0.53 | 0.64 | 0.73 | 0.80 | 0.86 | 0.87 | 0.93 |

**Table 5.8 Test Results of Expansion and Weight Change of the Concrete Prism (Lam Tei Quarry, 50% GGBS)**

| ML3 | Mix 4 - 50% GGBS + 50% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | -0.01 | -0.01 | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Weight change (%) | 0.23 | 0.33 | 0.42 | 0.52 | 0.59 | 0.67 | 0.73 | 0.69 | 0.76 | 0.84 |

**Table 5.9 Test Results of Expansion and Weight Change of the Concrete Prism (Lam Tei Quarry, 70% GGBS)**

| ML4 | Mix 5 - 70% GGBS + 30% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | -0.01 | -0.01 | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Weight change (%) | 0.21 | 0.26 | 0.37 | 0.48 | 0.59 | 0.61 | 0.71 | 0.75 | 0.77 | 0.80 |

**Table 5.10 Test Results of Expansion and Weight Change of the Concrete Prism (Lam Tei Quarry, 50% GGBS + 5% CSF)**

| ML5 | Mix 6 - 50% GGBS + 5% CSF + 45% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | -0.01 | -0.01 | 0.00 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Weight change (%) | 0.21 | 0.32 | 0.43 | 0.55 | 0.63 | 0.62 | 0.70 | 0.78 | 0.79 | 0.82 |

**Table 5.11 Test Results of Expansion and Weight Change of the Concrete Prism (Anderson Road Quarry, 100% Norcem)**

| MA0 | Mix 1 - 100% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | 0.00 | 0.00 | 0.02 | 0.07 | 0.10 | 0.11 | - | - | - | - |
| Weight change (%) | 0.24 | 0.29 | 0.33 | 0.36 | 0.37 | 0.37 | - | - | - | - |

**Table 5.12 Test Results of Expansion and Weight Change of the Concrete Prism (Anderson Road Quarry, 35% PFA)**

| MA1 | Mix 2 - 35% PFA + 65% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Weight change (%) | 0.23 | 0.36 | 0.45 | 0.53 | 0.64 | 0.71 | 0.63 | 0.63 | 0.60 | 0.67 |

**Table 5.13 Test Results of Expansion and Weight Change of the Concrete Prism (Anderson Road Quarry, 35% PFA + 5% CSF)**

| MA2 | Mix 3 - 35% PFA + 5% CSF + 60% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | -0.01 | -0.01 | -0.01 | -0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Weight change (%) | 0.20 | 0.31 | 0.38 | 0.44 | 0.49 | 0.59 | 0.67 | 0.70 | 0.80 | 0.82 |

**Table 5.14 Test Results of Expansion and Weight Change of the Concrete Prism (Anderson Road Quarry, 50% GGBS)**

| MA3 | Mix 4 - 50% GGBS + 50% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | -0.01 | -0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 |
| Weight change (%) | 0.24 | 0.35 | 0.45 | 0.56 | 0.64 | 0.73 | 0.80 | 0.86 | 0.87 | 0.91 |

**Table 5.15 Test Results of Expansion and Weight Change of the Concrete Prism (Anderson Road Quarry, 70% GGBS)**

| MA4 | Mix 5 - 70% GGBS + 30% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 |
| Weight change (%) | 0.26 | 0.32 | 0.46 | 0.59 | 0.71 | 0.74 | 0.84 | 0.85 | 0.88 | 0.89 |

**Table 5.16 Test Results of Expansion and Weight Change of the Concrete Prism (Anderson Road Quarry, 50% GGBS + 5% CSF)**

| MA5 | Mix 6 - 50% GGBS + 5% CSF + 45% Norcem | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Weeks | 2 | 4 | 13 | 26 | 44 | 52 | 65 | 78 | 91 | 104 |
| Elongation (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Weight change (%) | 0.25 | 0.30 | 0.38 | 0.49 | 0.59 | 0.60 | 0.70 | 0.74 | 0.72 | 0.75 |

# 6 Discussions

## 6.1 General

Summaries of the average expansions of all the mixes are given in Tables 5.5 to 5.16. As revealed from the expansion results, it can be seen that the expansions in the period are generally small and acceptable. The weights of specimens are increasing steadily.

## 6.2 Expansion of Concrete Prisms

The average expansions of the test specimens of each mix are shown in Figures 5.2 and 5.3. It can be seen that the average expansion of the control specimens (Norcem only) at 52 weeks are 0.11% and 0.12% for Anderson Road Quarry and Lam Tei Quarry respectively, which suggest that the aggregates in both quarries are ASR reactive. On the other hand, the maximum average expansions of the SCM specimens are 0.01% and 0.02% at 52 weeks and 104 weeks respectively. They are less than half of the threshold value 0.05%. It can be seen that the expansion of the specimens containing PFA is in general less than that of the specimens containing GGBS.

## 6.3 Weight Change

The average weight changes of the specimens of all mixes are shown in Figures 5.4 and 5.5. It is observed that the increase in the weight of the control specimens at 52 weeks is below 0.4%. For specimens containing SCM, the average increase in weight is around 0.6% at 52 weeks and it continues to increase steadily to nearly 0.8% at 104 weeks. Apparently, the weight may continue to further increase after 104 weeks.

The increase in the weights of specimens reveal that there may be chemical reactions being taking place in the concrete by absorbing the moisture or water from the wet cloths wrapped around the specimens. The possible chemical reactions may include (i) alkali-silica reaction, and (ii) secondary pozzolanic reaction. For slow or highly ASR reactive aggregates, the ASR may not yet be fully completed. Therefore, it is likely that both reactions are taking place concurrently. However, no obvious correlation between the weight increase and expansion have been observed. The type of chemical reaction can be investigated by using petrography after the completion of the laboratory investigation.

# 7 Specimens in an Outdoor Environment

In order to establish correlation(s) between the laboratory test results and the long term performance of SCM concrete made with local volcanic aggregates, field investigation will be carried out. For each of the six mixes (including one control mix), three concrete cylinder specimens were made using volcanic aggregates from the Anderson Road Quarry. Normal OPC from local market was used instead of Norcem.

A 12 mm diameter steel reinforcing bar is installed in the centre of each cylinder specimen. The cylinder specimens are stored in the open area of the rooftop of PWCL Building as shown in Figure 7.1.


**Figure 7.1 Cylinder Specimens Stored on the Rooftop of PWCL Building**

At quarterly intervals, inspections and measurements will be carried out on each cylinder specimen as presented below:

(1) Visual inspections for any signs of cracks;

(2) Height measurement at 0º, 90º, 180º and 270º;

(3) Diameter measurement at 0º, 90º 1/3 height and 0º, 90º 2/3 height; and

(4) Taking record photos.

According to overseas experience, it is common for ASR cracks to become visible on concrete structures containing reactive volcanic aggregates at around 10 years after construction. It is therefore expected that ASR cracks on the control specimens will be visible around or after 2025.

## 8 Conclusions and Recommendations

ASR has been known and got awareness by the industry practitioners in Hong Kong since early 90s. Thereafter, various studies and research have been undertaken to understand the detailed mechanisms involved as well as the mitigating measures and methods. The most common method is the addition of supplementary cementitious materials, like GGBS, PFA and CSF.

The PWCL has therefore carried out an investigation on the feasibility of mitigating the deleterious effects of ASR in concrete made with volcanic tuff aggregates from the Anderson Road Quarry and the Lam Tei Quarry in late 2014. A total of 12 different concrete mixes with various SCM replacement levels were studied in the investigation. Based on the results of concrete prism test up to 104 weeks, the following conclusions can be drawn:

(a) The PWCL's findings indicate that PFA (replacement level 35% or above) or GGBS (replacement level 50% or above) will be able to control the expansion to about 0.02%. When used in conjunction with silica fume, no obvious further reduction in expansion is found.

(b) According to Table 13 of Section 23 of CS1:2010, if the expansion after 52-week is less than 0.05%, the aggregates can be considered as ASR non-reactive. Therefore, the concrete mixes containing SCMs (i.e. PFA or GGBS or PFA+CSF or GGBS+CSF) under this laboratory investigation can be considered as ASR non-reactive.

(c) The findings also indicate that the weights of the test specimens are steadily increasing at about 0.4% per year during the investigation period, though the expansion of the specimens is around 0.01% per year. It is believed that the weight increase will continue. However, no obvious correlation between the weight increase and expansion have been observed. An extension of the test period for research purposes is recommended. The extension is not a requirement of any international practice or guidance to demonstrate the ASR non-reactiveness of the specimens. The results collected serve to enrich the understanding as to when weight increase will cease.

(d) At the end of the concrete prism test, it is recommended to conduct petrographic examination on the thin sections of the test specimens to check whether there is any sign of ASR.

(e) This study involves a single blend of volcanic aggregates, i.e. both coarse aggregates and fine aggregates are volcanic. It is highly desirable to have further studies on ASR effects of concretes made with various percentages or blends of volcanic aggregates with granite aggregates, because the rocks from local construction projects may contain granitic, volcanic, or other types of rocks.

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