Effectiveness of Traditional and Alternative Supplementary Cementitious Materials in Mitigating Alkali-Silica Reactivity

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Abstract: With occasional disruptions in the supply of quality fly ash, and the global move towards sustainable means of power generation, it is timely for the Australian construction industry to examine the use of alternative Supplementary Cementitious Materials (SCM's) in various concrete applications. In this study, Metakaolin, Ground Granulated Blast Furnace Slag and Fly Ash were used to partially replace traditional Portland cement in mortar mixtures. The influence of these SCM's on the workability and early age strength development of mortars was examined, along with their effectiveness in mitigating the alkali-silica reactivity (ASR) of aggregates, which was evaluated using the new Australian Standard AS1141.60.1 (1) for the Accelerated Mortar Bar Test (AMBT). Both the type and dosage of the two SCM's were studied.

Keywords: Accelerated mortar bar test (AMBT), alkali silica reactivity (ASR), supplementary cementitious materials (SCM).

1. Introduction

SCM's are not only widely used in concrete applications due to the range of benefits that such materials provide to the fresh and hardened properties of concrete, but also due to the range of environmental benefits associated with their use. With many SCM's being the by-product of existing and necessary industrial processes, the greenhouse gas emissions associated with the production of SCM's such as Fly Ash and GGBFS is considered to be negligible (Rubenstein (2)). The greenhouse gas emissions and energy requirements associated with the production of SCM's are attributed to the process from which the materials are wrought, and as such the use of certain SCM's is considered to be environmentally sustainable (Rubenstein (2)). In contrast, it is accepted that the production of 1 tonne of Portland cement results in emission of approximately 1 tonne of carbon dioxide alone, and as such, there is impetus within the construction industry to augment the use of blended cements and SCM's, which provide greater environmental sustainability (Rubenstein (2)).

Fly Ash and GGBFS are two of the most widely used and commercially available SCM's in Australia's construction industry, with Silica Fume also used in certain applications (Cement Australia 2014). With ongoing emphasis placed on the growth of sustainable energy production industries in Australia and on a global scale, it is estimated that the supply of Fly Ash to the Australian construction industry could halve by 2050 (Morrison, Graham et. al. (4)). In light of the popularity of the use of Fly Ash as a SCM, this paper seeks to present the effect that varying dosages of Fly Ash, GGBFS and an alternative SCM (Metakaolin) have on select fresh and hardened properties of mortars. This is crucial, as the findings of the report may deliver recommendations regarding types and dosages of SCM that can be used, should supply of traditional SCM's (namely Fly Ash) be constrained in the future.

The objectives of the reported work are as follows:

- To determine the impact of various dosages of Fly Ash, GGBFS and Metakaolin on early-age compressive strength of mortar, fresh properties (flow and air content) of mortar, and mitigation of mortar expansion due to alkali-silica reactions.
- If applicable, to propose types and dosages of SCM that can be used in concrete applications in place of Classified Fly Ash, (a commonly used SCM), should supply of Classified Fly Ash to the construction industry ever be constrained.
- To relate the mitigation of expansion of mortar bars due to alkali-silica reactions, to the physical and chemical characteristics of SCM's incorporated into mortars.
- To discuss variations in the compressive strength and workability of mortar specimens, in light of the physical and chemical properties of SCM's incorporated into mortars.

2 Scope and Experimental Procedures

With regards to the materials specifically used, two types of aggregate were tested:

- Dacite aggregate, denoted by 'DA'.
- Rhyolite aggregate, denoted by 'RH'.

These aggregates were used for the purposes of testing expansion of mortar due to ASR. For the determination of mortar air content and compressive strength, Sydney Sand was used as the fine aggregate; however, this is not denoted in the abbreviations used to identify such mortar mixtures.

Three types of SCM were tested: Fly Ash ('FA'), GGBFS ('SL') and Metakaolin ('MK').

Control mixtures, lacking any SCM, were also mixed and tested (denoted by the abbreviation, 'C').

2.1 Mix Design

Table 1: Mix Design Compositions for ASR Tests.

Mixture	*Cement (g)*	*SCM (g)*	*Aggregate (g)*	*Water (mL)*
DA-C	440	0	990	206.8
DA-FA10	396	44	990	206.8
DA-FA15	374	66	990	206.8
DA-FA25	330	110	990	206.8
DA-SL30	308	132	990	206.8
DA-SL40	264	176	990	206.8
DA-SL50	220	220	990	206.8
DA-MK7	409.2	30.8	990	206.8
DA-MK10	396	44	990	206.8
DA-MK15	374	66	990	206.8
RH-C	440	0	990	206.8
RH-FA10	396	44	990	206.8
RH-FA15	374	66	990	206.8
RH-FA25	330	110	990	206.8
RH-SL30	308	132	990	206.8
RH-SL40	264	176	990	206.8
RH-SL50	220	220	990	206.8
RH-MK7	409.2	30.8	990	206.8
RH-MK10	396	44	990	206.8
RH-MK15	374	66	990	206.8

Table 2: Mix Design Compositions for compressive strength, mortar flow and mortar air content tests.

Mixture	*Cement (g)*	*SCM (g)*	*Aggregate (g)*	*Water (mL)*
C	447.2	0	1229.7	268.3
FA10	402.5	44.7	1229.7	268.3
FA15	380.1	67.1	1229.7	268.3
FA25	335.4	111.8	1229.7	268.3
SL30	313	134.2	1229.7	268.3
SL40	268.3	178.9	1229.7	268.3
SL50	223.6	223.6	1229.7	268.3
MK7	415.9	31.3	1229.7	268.3
MK10	402.5	44.7	1229.7	268.3
MK15	380.1	67.1	1229.7	268.3

2.2 Experimental Methodology

Expansion of mortar bars due to ASR was tested and determined in line with AS1141.60.1-14 (1).

Flow of fresh mortar was measured in accordance with ASTM C1437-13 (5). Air content of fresh mortar was measured in line with ASTM C185-08 (6). Compressive strength of mortar cube specimens was determined in line with ASTM C109/C109M-13 (7).

Experimental conditions and methodologies which are referenced in the aforementioned standards, were followed where applicable.

3.0 Results and Discussion

3.1 Alkali-Silica Reactivity

Table 3: Mean expansion of mortar bars of different ages (Dacite aggregate).

	Expansion (%) at age						
Mixture	***3-d***	***7-d***	***10-d***	***14-d***	***21-d***	***28-d***	***35-d***
DA-C	0.020	0.155	0.269	0.397	0.565	0.691	0.791
DA-FA10	0.011	0.059	0.113	0.180	0.286	0.367	0.432
DA-FA15	0.007	0.017	0.031	0.055	0.109	0.160	0.208
DA-FA25	-0.001	0.001	0.007	0.011	0.020	0.030	0.047
DA-SL30	0.017	0.079	0.132	0.200	0.290	0.359	0.414
DA-SL40	0.012	0.045	0.075	0.116	0.179	0.228	0.273
DA-SL50	0.002	0.013	0.020	0.031	0.060	0.090	0.118
DA-MK7	0.020	0.117	0.191	0.277	0.395	0.482	0.548
DA-MK10	0.015	0.081	0.135	0.200	0.293	0.367	0.422
DA-MK15	0.007	0.020	0.033	0.051	0.087	0.127	0.157

Table 4: Mean expansion of mortar bars of different ages (Rhyolite aggregate).

	Expansion (%) at age						
Mixture	***3-d***	***7-d***	***10-d***	***14-d***	***21-d***	***28-d***	***35-d***
RH-C	0.013	0.073	0.147	0.228	0.324	0.393	0.451
RH-FA10	0.010	0.026	0.041	0.070	0.117	0.159	0.191
RH-FA15	0.004	0.012	0.019	0.025	0.037	0.053	0.074
RH-FA25	0.001	0.005	0.011	0.012	0.017	0.021	0.028
RH-SL30	0.013	0.037	0.059	0.095	0.150	0.186	0.223
RH-SL40	0.013	0.027	0.035	0.051	0.083	0.107	0.136
RH-SL50	0.003	0.012	0.016	0.022	0.033	0.042	0.059
RH-MK7	0.013	0.055	0.108	0.167	0.239	0.297	0.338
RH-MK10	0.010	0.038	0.069	0.112	0.170	0.221	0.257
RH-MK15	0.007	0.017	0.023	0.032	0.047	0.070	0.085

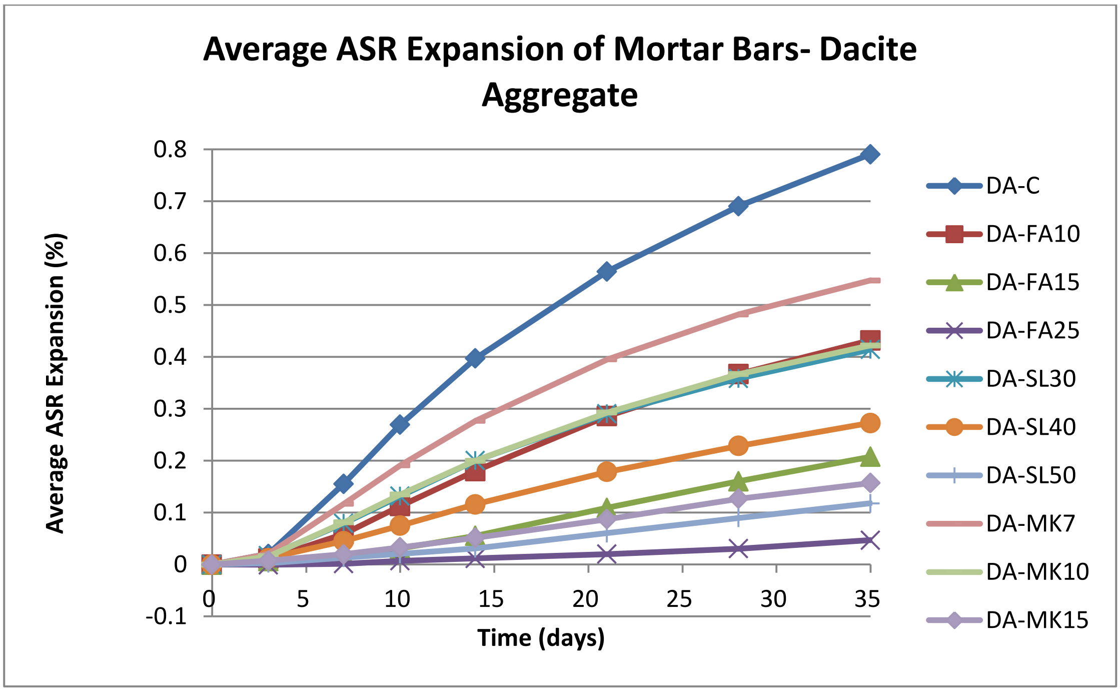

Figure 1: Average ASR expansion of mortar bars- Dacite aggregate.

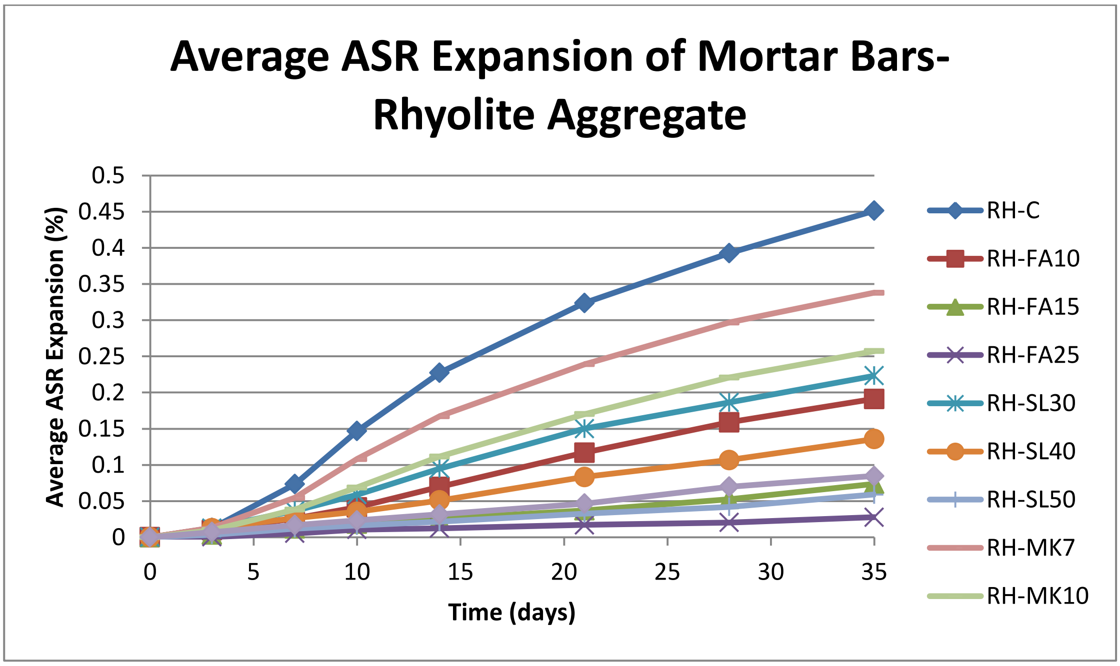

Figure 2: Average ASR expansion of mortar bars- Rhyolite aggregate.

Figures 1 and 2 above indicate that the expansion due to ASR of mortar bars containing Fly Ash increases at a decreasing rate with time, regardless of the type of aggregate used. It is expected that expansion of mortar bars containing Fly Ash as partial replacement of Portland cement would continue to increase with time in the accelerated mortar bar test. This is due to the saturation of mortar bars with sodium hydroxide solution, which provides an abundance of alkalis able to penetrate into the mortar mixture to facilitate alkali-silica reactions (Thomas (8)). However, the decreasing rate of expansion of mortar bars containing Fly Ash is attributed to the pozzolanic reaction associated with Fly Ash. An abundance of experimental work and literature exists, which outlines the efficacy of Fly Ash in consuming calcium hydroxide within mortars, thus reducing the alkali content of the mortar and mitigating the alkali-silica reaction (Kandasamy & Shehata (9); Shafaatian, Akhavan et al. (10)). Not only does the pozzolanic reaction allow Fly Ash to bind alkalis via this chemical reaction, but it also results in the formation of secondary C-S-H gel, which prevents the dissolution of soluble calcium hydroxide with free water in the mortar mixture (Kandasamy & Shehata (9)). Dissolution of calcium hydroxide would otherwise increase the alkali concentration within the mortar mixture, facilitating the alkali-silica reaction (Kandasamy & Shehata (9)). Whilst effects of the pozzolanic reaction are noticeable after the age of 28-d, (and sometimes do not become prevalent prior to 90-d) (Sumer (11)), Figures 1 and 2 above indicate that at an age as low as 14-d, the rate of expansion of mortar bars containing Fly Ash begins to visibly decrease (evident as the gradient lines showing the mean expansion of each mortar bar begins to plateau).

The results indicate that the efficacy of GGBFS in mitigating expansions due to ASR became more prevalent with time, a likely indication of the pozzolanic reaction of GGBFS beginning. As Figures 1 and 2 demonstrate, at the early age of 3-d, the use of 40% GGBFS to replace Portland cement (using the Dacite aggregate) was not as efficacious in mitigating expansion of mortar bars due to ASR as mortars containing any dosage of Fly Ash, 50% GGBFS or 15% Metakaolin. Figures 1 and 2 also show that at the early age of 3-d, the use of 30% GGBFS to replace Portland cement was ineffective in curtailing expansion due to ASR, with all other mortar mixtures recording smaller expansion values, with the exception of the control mixture and the mixture containing 7% Metakaolin (when the Dacite aggregate was used). When the Rhyolite aggregate was used, mortar mixtures containing both 30% and 40% GGBFS were ineffective in curtailing expansion due to ASR at 3-d, with these mixtures recording the same expansion as the control. It is postulated that any initial benefits (or lack thereof), of GGBFS in mitigating expansion due to ASR can be attributed to the dilution of alkalis in the pore solution of mortars, associated with the use of GGBFS. At the early age of 3-d, the pozzolanic reaction associated with GGBFS has not had time to initiate, and thus, mitigation of expansion due to ASR associated with GGBFS mixtures, results from a reduction in the net quantity of available, soluble alkalis in the mortar pore solution (Kandasamy & Shehata (9); Kwon (12)). Regardless of the aggregate used, results indicate that incorporation of 50% GGBFS into a mortar mixture is able to sufficiently reduce the quantity of alkalis present in the mortar pore solution. However, the use of 30% and 40% GGBFS in mortar mixtures is less efficacious in achieving this end.

Being an artificial pozzolan, Metakaolin consumes portlandite and calcium hydroxide contained within the pore solution of cement paste, producing secondary C-S-H gel (Ramlochan, Thomas et. al. (13)). In doing so, the Metakaolin directly consumes alkalis, removing them from the pore solution of the cement paste, thus minimising the quantity of available alkali which is able to react with reactive silica introduced into the mortar mixture (Thomas (8), Ramlochan, Thomas et. al. (13)). When the Rhyolite aggregate was tested, the use of 15% Metakaolin was also highly effective, with only the expansion of mortar bars containing 15% Fly Ash, 25% Fly Ash or 50% GGBFS being less at 21-d. It is clear that as the dosage of Metakaolin used to partially replace Portland cement increases, the mitigation of expansion due ASR in mortar bars is enhanced. Not only is the retention of alkalis significant in the mitigation of ASR, but in the case of Metakaolin, so too is the retention of calcium, freely present in the pore solution of mortars. When alkali-silica gel forms, its expansion is widely attributed to the consumption of calcium (in the form of calcium hydroxide) (Thomas (8); Aquino, Lange et. al. (14)). Rather than forming an alkali-silica gel of low viscosity, which permeates into mortar pores with little expansive pressure, the consumption of calcium hydroxide creates a hygroscopic alkali-silica gel, which absorbs free water, expanding in the process (Thomas (8); Aquino, Lange et. al. (14)).

As shown in Figures 1 and 2 above, the use of 7% or 10% Metakaolin to partially replace Portland cement was relatively ineffective in mitigating ASR expansion, regardless of the type of aggregate used. Regardless of the aggregate used, the use of 10% Metakaolin in mortars recorded expansion lower than only the control mixture, and the mortar containing 7% Metakaolin. At the age of 28-d, the 10% Metakaolin mixture recorded expansion which was less than that of mortar containing 30% GGBFS, and equal to that of mortar containing 10% Fly Ash, an indication of the pozzolanic reaction of Metakaolin taking effect. The use of 7% Metakaolin was the most ineffective mortar mixture (with regards to the type and dosage of SCM used), as it recorded expansion values greater than those of all mortar mixtures, with the exception of the control mixture (regardless of the aggregate used). Ramlochan, Thomas et. al. (13)) have shown experimentally, that the incorporation of less than 10% Metakaolin into a mortar mixture results in the formation of additional portlandite between the ages of 14-28-d (Ramlochan, Thomas et. al. (13)). This results because, once all the available Metakaolin has experienced the pozzolanic reaction, further calcium hydroxide ions are produced from subsequent hydration reactions in the mortar (Ramlochan, Thomas et. al. (13)). With time, this portlandite is able to leach alkalis into the mortar pore solution, facilitating the formation of expansive ASR gel (Ramlochan, Thomas et. al. (13)). Although this investigation did not seek to determine the alkali concentration of mortar bars containing dosages of various SCM's, let alone the portlandite content of such mortars, the ASR expansion results obtained for mortar bars containing 7% Metakaolin would seem to support the findings of Ramlochan, Thomas et. al. (13). The lack of efficacy of 7% Metakaolin in mitigating ASR expansion can likely be attributed to its high reactivity (its high alumina content, relative to Fly Ash, GGBFS and Portland cement contributes to its pozzolanic properties). Consequently, Metakaolin is unable to effectively mitigate the formation of portlandite, and expansive alkali-silica gel with time, when used in small dosages.

3.2 Early-Age Compressive Strength

Table 5: Effect of SCM type/dosage on mean 7-d and 28-d compressive strength of mortars.

Mortar Mixture	*7-d Compressive Strength (MPa)*	*28-d Compressive Strength (MPa)*
C	24.0	36.0
FA10	18.0	37.0
FA15	19.5	38.0
FA25	17.5	36.5
SL30	18.0	36.0
SL40	18.0	30.0
SL50	16.5	26.0
MK7	20.5	34.5
MK10	20.5	37.0
MK15	24.0	37.0

As shown in Table 5, the fact that the mortar containing 15% Fly Ash records the greatest 7-d compressive strength of all mortars containing Fly Ash is attributed to the role of the dilution and filler effects at this early age. The filler and dilution effects have greater impact as the dosage of Fly Ash increases. As such, where 10% Fly Ash is used, the filler effect has a negligible impact on compressive strength, with the 24.5% decrease in 7-d compressive strength attributed to the dilution of the total quantity of Portland cement within the mortar, via partial replacement with Fly Ash. The compressive strength of mortars containing 25% Fly Ash is also decreased, due to the precedence that the dilution effect takes, over the filler effect in contributing to (inhibiting) compressive strength (which explains the 27% decrease in compressive strength at 7-d associated with this dosage). It would seem that the use of 15% Fly Ash represents an optimum dosage, whereby decreases in strength associated with the dilution effect are counteracted by compressive strength increases attributed to the filler effect. The fact that mortars containing 15% Fly Ash recorded the smallest decrease in 7-d compressive strength compared to other Fly Ash mixtures would seem to compliment this explanation.

The lack of early-age strength development exhibited by mortar mixtures containing GGBFS is attributed to both the slow onset of the pozzolanic reaction, and the dilution effect, a phenomenon especially prevalent due to the large dosages of GGBFS used to partially replace Portland cement. As GGBFS was used to partially replace Portland cement in dosages ranging from 30-50% in this investigation, the contributions that the filler effect and cementitious properties of GGBFS provided to the early-age strength development of mortar were outweighed by the dilution effect of the SCM. Due to the significant mass of GGBFS used to replace Portland cement in each mortar mixture, the total quantity of cementitious material able to contribute to the early-age strength development of the mortar decreases relative to the control mixture containing Portland cement alone (Barnett, Soutsos et al. (14)). The results shown in Table 5 above compliment this academic finding, whereby the compressive strength at both 7-d and 28-d of mortars containing GGBFS was reduced relative to that of the control mortar. Due to the dilution effect in particular, as the dosage of GGBFS used to partially replace Portland cement in mortar increases, inversely, the compressive strength of the mortar decreases (Miyazawa, Yokomuro et. al. (16)).

Metakaolin has a ‘filling effect’ when used in mortar, whereby, the small particle fineness and high specific surface area of the Metakaolin allows the SCM to fill voids between un-hydrated cement particles and aggregate particles in the mortar (Guneyisi, Gesoglu et. al. (17)). This allows the formation of a mortar with a dense microstructure, which is relatively free of capillary pores, providing strength to the mortar. With a particle fineness approximately 40 times that of Portland cement, Metakaolin particles are able to pack the interfacial transition zone between cement paste and aggregate particles in mortar, filling voids and capillary pores. This increases the density of the microstructure of the mortar, whilst homogenously dispersing cementitious by-products throughout the interfacial transition zone of the mortar (Wild, Khatib et. al. (18)). The filler effect that Metakaolin provides is understood to outweigh the dilution effect associated with the SCM (Guneyisi, Gesoglu et. al. (17); Wild, Khatib et. al. (18)), allowing it to enhance the strength of mortar when used in dosages ranging from 5-15%. The results shown in Table 5 above compliment this academic finding, and in particular, explain the high 7-d compressive strength of mortar specimens containing Metakaolin, relative to mortars containing Fly Ash and GGBFS.

Being a predominately alumino-siliceous material, Metakaolin displays pozzolanic characteristics. Consequently, the material is able to hydrate and harden in the presence of moisture in mortar, consuming calcium hydroxide within the mortar pore solution to produce C-S-H gel, which contributes to the strength development of the mortar (Guneyisi, Gesoglu et. al. (17)). Despite having high contents of reactive silica and alumina relative to Portland cement (Megat Johari, Brooks et. al. (19)), the pozzolanic reactions associated with Metakaolin are most vigorous between the ages of 7-d to 14-d (Wild, Khatib et. al. (18)). This academic finding is supported by the experimental results presented in this investigation, whereby, the 28-d compressive strength of mortar specimens containing Metakaolin was found to be greater than that of the control mixture (with the exception of the mortar mixture containing 7% Metakaolin).

3.3 Mortar Flow

Table 6: Effect of SCM type and dosage on fresh mortar flow.

Mortar Mixture	***C***	***FA10***	***FA15***	***FA25***	***SL30***	***SL40***	***SL50***	***MK7***	***MK10***	***MK15***
Flow (%)	132	135	136	137	129	139	133	136	126	126

The results shown in Table 6 compliment a plethora of academic studies, which present experimental results that correlate increases in mortar flow with increasing dosages of Fly Ash. According to Sumer (11), "the morphologic effect states that there are many micro beads in Fly Ash, working as 'lubricating balls' when incorporated in fresh concrete" (Sumer 2012, p.531 (11)). The spherical shaped particles that constitute Fly Ash induce a 'ball bearing effect' regarding the fluidity and motion of mortar in the fresh state, which is manifested by way of enhanced workability (increasing mortar flow), when the Fly Ash is incorporated into a mortar mixture. This explanation is supported by Sahmaran, Christianto et. al.(20), who argue that the spherical shape of Fly Ash particles reduces friction between the particles themselves, Fly Ash and cement particles, and Fly Ash and aggregate particles in a mortar mixture, enhancing mortar flow. Consequently, when force is exerted on a mortar or concrete mixture during placement and consolidation, the decreased resistance to particle motion (aided by the lessened frictional forces acting between the cementitious paste and aggregate particles) improves the workability of the mixture. With regards to mortar, this phenomenon is manifested through a noticeable increase in the flow of mortars containing Fly Ash.

The increase in flow associated with mortars containing 40% and 50% GGBFS, as shown in Table 6, is indicative of other experimental and academic studies. As the dosage of GGBFS used to replace Portland cement was increased, so too did mortar flow. This is attributed to the smooth, glass-like texture of GGBFS, which allows the SCM to increase mortar flow, despite its angular and irregular particle shape (Sumer (11); Isikdag & Topcu (21)). A significant body of academic study indicates that GGBFS also disperses cementitious particles evenly in a mortar matrix, which enhances the flow of such mixtures (Megat Johari, Brooks et al. (19)). The improved workability that GGBFS provides to mortar (in the correct dosages) is also attributed to the particle size of GGBFS particles, which provides a micro bead effect within the mortar (Sumer (11)).

The results obtained compliment numerous academic studies, which show that as the dosage of Metakaolin used to partially replace Portland cement in mortar mixtures increases, the flow of the mortar mixtures decreases. This is primarily attributed to the water demand that Metakaolin particles exhibit, which is a combination of both the fineness and morphology of the material (Wild, Khatib et. al. (18); Siddique & Klaus (22)). With an average specific surface area of 15000 m^2/kg (Megat Johari, Brooks et. al. (19)), Metakaolin has a specific surface area significantly higher than that of Portland cement (380 m^2/kg). Consequently, Metakaolin exhibits a high water demand when introduced into mortar, absorbing mix water, and thus preventing the mix water from contributing to the fluidity and flow of the mortar (Wild, Khatib et. al. (18)).

3.4 Mortar Air Content

Table 7: Effect of SCM type and dosage on air content of mortar.

Mortar Mixture	***C***	***FA10***	***FA15***	***FA25***	***SL30***	***SL40***	***SL50***	***MK7***	***MK10***	***MK15***
Air Content (%)	3.5	4.2	4.3	4.3	4.7	4.5	4.2	4.6	4.4	3.9

As the results in Table 7 above indicate, the partial replacement of Portland cement with Fly Ash, GGBFS or Metakaolin increases the air content of mortar, relative to the control mixture. As the dosage of GGBFS and Metakaolin used to partially replace Portland cement in a mortar mixture increases, the air content of the mortar mixture decreases. This is attributed to the 'filler effect' associated with both these SCM's. The small particle size of GGBFS, and in particular, Metakaolin, relative to that of Portland cement, allows the SCM's to penetrate homogenously throughout the microstructure of a mortar mixture, refining the size of microstructural pores within the mortar (Guneyisi, Gesoglu (17); Wild, Khatib et. al. (18); Siddique & Klaus (22)). Consequently, the volume of air retained within the pores of the mortar decreases, due to the enhanced microstructural density of the mortar which results (Guneyisi, Gesoglu (17); Wild, Khatib et. al. (18); Siddique & Klaus (22)). It is postulated that greater microstructural density and mortar pore refinement is associated with an increase in the dosage of GGBFS or Metakaolin incorporated into a mortar mixture. In turn, the air content of the mortar would be expected to decrease, a postulation complimented by the experimental data obtained.

The increase in the air content of mortar mixtures containing increasing dosages of Fly Ash (as a partial replacement for Portland cement) presents a counter-intuitive result. In line with academic findings, it was anticipated that, as the dosage of Fly Ash used to partially replace Portland cement was increased, the air content of the mortar mixtures would decrease. Such results would be attributed to the filler effect, whereby, the micro bead effect associated with Fly Ash allows the material to enhance the microstructural density of mortar, by penetrating homogenously throughout a mortar mixture (Sumer (11)). The results obtained do not compliment current academic findings. As such, it is postulated that the particle-packing behaviour of the spherical Fly Ash particles influenced the air content of the mortar mixtures which resulted. When spherical Fly Ash particles pack within a mortar mixture, voids form between the particles, in which air can become entrapped.

4.0 Conclusions

Due to the need to address potential constraints regarding the supply of Fly Ash to the construction industry (for use in concreting applications), the results and discussion presented in this investigation indicate that dosages of GGBFS and Metakaolin can be used to partially replace Portland cement in concrete applications, rather than the more traditionally used Fly Ash. Furthermore, the experimental results presented in this report, outline that particular dosages of Fly Ash, GGBFS and Metakaolin can also be used to partially replace Portland cement in concreting applications, for the purposes of preventing expansion due to alkali-silica reactivity, without having deleterious effects on the early-age compressive strength, flow or air content of mortars. The following core results were found:

- 25% replacement of Portland cement with Fly Ash ought to ensure the mitigation of expansion due to alkali-silica reactivity. Whilst the use of 25% Fly Ash is not the dosage which optimises the 28-d compressive strength of mortar, this dosage will increase the 28-d compressive strength of concrete, relative to a control specimen. Furthermore, the use of 25% Fly Ash is also expected to enhance the workability of concrete in the fresh state, namely, flow and air content. Where such a dosage was used in this investigation, the air content of mortar was found to increase by 22.9%, and the flow of mortar was found to increase by 3.8%, indicating an increase in the ease with which concrete containing 25% Fly Ash can be placed and consolidated in the fresh state.
- 50% replacement of Portland cement with GGBFS ought to ensure the mitigation of expansion due to alkali-silica reactivity. It is not recommended that GGBFS be used in applications where

it is necessary to mitigate expansion due to alkali-silica reactivity, whilst also maintaining or enhancing the compressive strength of the concrete in question. This is because it is expected that using such a dosage (50%) of GGBFS, will decrease the 28-d compressive strength of concrete. Thus, concrete containing 50% GGBFS should not be used in high strength concreting applications. However, 50% GGBFS was found to enhance the workability (air content and flow) of mortars, which is desirable regarding fresh concrete. In particular, this dosage of GGBFS was found to enhance mortar air content by 20%, and flow by 0.8%, relative to the control, in this investigation.

- 15% replacement of Portland cement with Metakaolin ought to ensure the mitigation of expansion due to alkali-silica reactivity. This is ideal, as the use of 15% Metakaolin ought to maximise the 28-d compressive strength of mortar. In this investigation it was found that the use of 15% Metakaolin enhanced the 28-d compressive strength of mortar by 3.4%, relative to the control. However, the use of 15% Metakaolin has mixed effects on the workability of mortar in the fresh state. The use of 15% Metakaolin can be expected to enhance the air content of mortars (an increase of 11.4% relative to the control was noted in this investigation). However, the use of 15% Metakaolin significantly increases the water demand of mortar mixtures, and as such, decreases the flow of mortar in the fresh state.

As stated, the aforementioned dosages of Fly Ash, GGBFS and Metakaolin ought to be used in practice, so as to mitigate deleterious expansion of concrete elements due to alkali-silica reactivity. In summation, it is evident that, in the correct dosage, Fly Ash, GGBFS and Metakaolin can all be used to optimise the mitigation of ASR expansion, early-age compressive strength development, and the flow and air content of fresh mortars, and as such, these SCM's can find application in concrete practice within the Australian construction industry.

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6.0 References

1. Standards Australia 2014, *Methods for sampling and testing aggregates- Potential alkali-silica reactivity- Accelerated mortar bar method*, AS 1141.60.1-2014, Standards Australia, Sydney.

2. Rubenstein, M. 2012, *Emissions from the cement industry*, State of the Planet, accessed 20 October 2014, http://blogs.ei.columbia.edu/2012/05/09/emissions-from-the-cement-industry/.

3. Cement Australia 2014, *Why do we use Supplementary Cementitious Materials (SCM's)?,* Cement Australia, accessed 22 September 2014, http://www.cementaustralia.com.au/wps/wcm/connect/website/bulk/bulk-home/faqs/#FAQ-bulk-q15.html.

4. Morrison, A., Graham, P. & Nelson, P.F. 2005, 'Future ash availability- Potential consequences of transformation of Australia's energy generation portfolio to 2050', 2005 World of Coal Ash (WOCA), Lexington, viewed 20 October 2014, http://www.flyash.info/2005/88mor.pdf.

5. American Society for Testing and Materials 2013, *Standard Test Method for Flow of Hydraulic Cement Mortar*, ASTM C1437-13, American Society for Testing and Materials, Pennsylvania.

6. American Society for Testing and Materials 2008, *Standard Test Method for Air Content of Hydraulic Cement Mortar*, ASTM C185-08, American Society for Testing and Materials, Pennsylvania.

7. American Society for Testing and Materials 2013, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (using 2-in. or [50-mm] Cube Specimens)*, ASTM C109/C109M-13, American Society for Testing and Materials, Pennsylvania.

8. Thomas, M. 2011, 'The effect of supplementary cementing materials on alkali-silica reaction: A review', *Cement and Concrete Research*, vol. 41, no. 12, pp. 1224-1231.

9. Kandasamy, S. & Shehata M.H. 2014, 'The capacity of ternary blends containing slag and high-calcium fly ash to mitigate alkali silica reaction', *Cement and Concrete Composites*, vol. 49. May 2014, pp. 92-99.

10. Shafaatian, S.M.H., Akhavan, A., Maraghechi, H. & Rajabipour, F. 2013, 'How does fly ash mitigate alkali-silica reaction (ASR) in accelerated mortar bar test (ASTM C1567)?' *Cement and Concrete Composites*, vol. 37, March 2013, pp. 143-153.

11. Sumer, M. 2012, 'Compressive strength and sulfate resistance properties of concretes containing class F and class C fly ashes', *Construction and Building Materials*, vol. 34, September 2012, pp. 531-536.

12. Kwon,Y-J. 2005, 'A study on the alkali-aggregate reaction in high strength concrete with particular respect to the ground granulated blast-furnace slag effect', *Cement and Concrete Research*, vol. 35, no. 7, pp. 1305-1313.

13. Ramlochan, T., Thomas, M. & Gruber, K.A. 2000, 'The effect of metakaolin on alkali-silica reaction in concrete', *Cement and Concrete Research*, vol. 30, no. 3, pp. 339-344.

14. Aquino, W., Lange, D.A. & Olek, J. 2001, 'The influence of metakaolin and silica fume on the chemistry of alkali-silica reaction products', *Cement and Concrete Composites*, vol. 23, no. 6, pp. 485-493.

15. Barnett, S.J., Soutsos, M.N., Millard, S.G. & Bungey, J.H. 2006, 'Strength development of mortars containing ground granulated blast-furnace slag: Effect of curing temperature and determination of apparent activation energies', *Cement and Concrete Research*, vol. 36, no. 3, pp. 434-440.

16. Miyazawa, S., Yokomuro, T., Sakai, E., Yatagai, A., Nito, N. & Koibuci, K. 2014, 'Properties of concrete using high C_3S cement with ground granulated blast-furnace slag', *Construction and Building Materials*, vol. 61, June 2014, pp. 90-96.

17. Güneyisi, E., Gesoğlu, M., Karaoğlu, S. & Mermerdaş, K. 2012, 'Strength, permeability and shrinkage cracking of silica fume and metakaolin concretes', *Construction and Building Materials*, vol. 34, September 2012, pp. 120-130.

18. Wild, S., Khatib, J.M. & Jones, A. 1996 'Relative strength, pozzolanic activity and cement hydration in superplasticized metakaolin concrete', *Cement and Concrete Research*, vol. 26, no. 10, pp. 1537-1544.

19. Megat Johari, M.A., Brooks, J.J., Kabir, S. & Rivard, P. 2011, 'Influence of supplementary cementitious materials on engineering properties of high strength concrete', *Construction and Building Materials*, vol. 25, no. 5, pp. 2639-2648.

20. Sahmaran, M., Christianto, H.A. & Yaman, I.O. 2006, 'The effect of chemical admixtures and mineral additives on the properties of self-compacting mortars', *Cement and Concrete Composites*, vol. 28, no. 5, pp. 432-440.

21. Isikdag, B. & Topcu, I.B. 2013, 'The effect of ground granulated blast-fruance slag on properties of Horasan mortar', *Construction and Building Materials*, vol. 40, March 2013, pp. 448-545.

22. Siddique, R. & Klaus, J. 2009, 'Influence of metakaolin on the properties of mortar and concrete: a review', *Applied Clay Science*, vol. 43, no. 3-4, pp. 392-400.