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THE INFLUENCE OF CEMENT REPLACEMENT MATERIALS ON THE FLEXURAL BOND STRENGTH OF MASONRY

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Abstract

This paper reports on an experimental study of the influence on bond strength of partial Portland cement replacement in mortar. The replacement materials used were either ground granulated blast furnace slag (GGBS) or fly ash (FA). Two mortar types were used, 1:1:6 (cement:lime:sand by volume) and 1:0:5 (with a methyl cellulose additive), in conjunction with high and low suction fired clay units. Bond strengths of masonry joints were obtained at 7 and 28 days using the bond wrench. In all cases, reduced bond strengths were obtained for varying proportions of GGBS and FA replacement. However, the strengths obtained for all blend proportions were still greater than the default bond strength values assumed in the Australian Masonry Code. Detailed results are presented and the causes of strength variations discussed.

Key Words: masonry bond strength, Portland cement, blended cement, hydrated lime

1 Introduction

The production of Portland cement involves the blending and grinding of raw materials, calcination at 1500ºC, followed by the controlled cooling and grinding of the clinker product. This is an energy-intensive process and requires approximately 4000 MJ/t of cement (Shi et al, 2000). Industry by-products such as blast furnace slag and fly ash can be used as partial cement replacement materials, due to their cementitious or pozzolanic nature, and when mixed with Portland cement, the material is referred to as "blended cement". This is an environmentally attractive reuse of industry by-products

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since it decreases the need for landfill disposal and the overall energy required in production of the cementitious blends. The partial replacement of cement with these by-products may decrease the early strength of the binder, but increases the later strength whilst improving microstructure and durability of hydrated cement paste. Blended cements are widely used in the concrete industry and in masonry mortar applications. Due to variations in chemical and physical properties of cement replacement materials, blended cements must meet specific criteria including compressive strength, setting time and soundness requirements. In Australia, these are outlined in AS3972 (Standards Australia, 1997).

In masonry applications, the achievement of an effective mortar to unit bond is an important aspect of construction in order to impart structural integrity and durability to the masonry assemblage. Bond formation is the result of complex interactions and is dependant on material characteristics, workmanship, curing environment and age. The results of an extensive bond strength investigation involving the use of commercially available Portland cement and blended cement products have been reported previously (Page et al, 2003). This previous investigation considered numerous mortars and masonry unit types. Bond strengths were monitored over a two year period under internal/external curing conditions. The work showed that there were several interactions between the different cements/units/mortars and age. This investigation is an extension of the previous work focusing on the systematic replacement of GP cement by ground granulated blast furnace slag (GGBS) and fly ash (FA) materials and their subsequent influence on bond strength. This was achieved using laboratory derived cement blends, with higher proportions of cement replacement material being used than for those found in commercial cement blends. The investigation was carried out using high and low suction masonry clay units and two different mortar types. Bond strength was evaluated using the bond wrench test at 7 and 28 days. Further work on effects of long-term age, microstructure development and mortar durability (Testone et al, 2004) are being undertaken.

2 Experimental Procedure

Commercial grade cement replacement materials (GGBS and FA) were sourced for the investigation together with a General Purpose Portland cement (GP). The hydrated lime used was also a commercial product. The bulk densities of GP cement, lime, GGBS and FA were 1.21, 0.54, 0.99 and 0.85x10^3 kg/m^3, respectively. The sand was a washed dune sand with a bulk density of 1.47x10^3 kg/m^3. The particle size distribution is shown in Table-1. Despite the narrow size distribution and lack of fines, this sand is used in masonry mortars due to its ready availability in the Newcastle area.

Table-1. Particle Size Distribution of Dune Sand

Sieve Size	2.36 mm	1.18 mm	600 μm	300 μm	150 μm	75 μm
Passing [%]	100	100	96	25	1	0

Two types of masonry clay units were used. One was a low suction extruded unit (IRA= 0.71kg/m^2/min) and the other high suction dry pressed brick (IRA= 5.24kg/m^2/min). The cold water absorption and 5 hour boil absorption of the units were determined to be 3.4% and 4.8% for the extruded bricks and, 10.7%, 13.5% for the dry pressed bricks respectively. These properties were determined in accordance with AS/NZS4456 (Standards Australia, 2003).

The mortars used in the study were a 1:1:6 (cement:lime:sand by volume) and a 1:0:5 mortar containing a methyl cellulose additive (0.005 parts by weight of binder). These mortars are widely used in masonry construction. The proportion of the GP cement

component in each initial mortar was systematically replaced by GGBS or FA in steps of 10% (by volume). The maximum proportion of GGBS blend was 70% (by volume) replacement of GP cement and for FA the corresponding limit was 60% (by volume), resulting in 28 different mortar mixes. It was found that increasing amounts of GGBS or FA caused the mortar to bleed and exhibit reduced workability. The reduction in workability was more noticeable with the FA mortars and governed the upper limits of the cement replacement materials for the study. For each batch, the amount of water added during mixing was adjusted by the mason to obtain the best possible workability. The fresh mortar properties of flow and gravimetric air content were determined in accordance with AS2701 (Standards Australia, 2001).

From each of 28 different mortar mixes, four 6-high stack-bonded masonry prisms were prepared with each particular type of unit providing ten joints for each age. The flexural bond strength of masonry was determined at 7 and 28 days by bond wrench test in accordance with AS3700 (Standards Australia, 2001). Prior to testing, the specimens were cured in the laboratory under plastic sheeting. Initial and final setting time, normal consistency and compressive strength tests were also conducted on the GP and upper limit blends in accordance with AS/NZS 2350 (Standards Australia, 1999) for compliance with AS3972 (Standards Australia, 1997).

3 Results

3.1. Fresh Mortars Properties

The fresh mortar properties of flow, gravimetric air content and water/binder ratios are presented in Table-2 and Table-3 for the 1:1:6 mortars and 1:0:5 mortars respectively. From the results in the Table-2 it can be observed that adequate workability of GGBS or FA containing mortars was achieved at higher flow values than the reference mortar 1:1:6 (without the cement replacement material). However, the amount of added water decreased slightly with increasing GGBS content and was approximately constant with increasing proportions of the FA. The increasing water/binder ratio with increasing cement replacement material observed in Table-2 is due to the reduced mass of binder in the batch with increasing of GGBS or FA content. This is a result of the lower bulk density of the cement replacement materials combined with the volume based mortar batching procedure. The gravimetric air content of the mortars with GGBS was in the narrow interval between 3.2% and 3.5% (with one exception). For the fly ash mortars, the air content decreased steadily from 3.1% at 10% GP replacement down to 1.4% at 60% GP replacement. In both cases the air content was much lower than the 6.3% air content of the reference 1:1:6 mortar.

Table-2: Fresh properties of the 1:1:6 mortars.

Replacement of cement [% by volume]	Replacement by GGBS			Replacement by fly ash		
	Water/Binder ratio	Flow [%]	% Air content	Water/Binder ratio	Flow [%]	% Air content
0*	1.66	130	6.3	1.66	130	6.3
10	1.90	150	3.5	1.86	>150	3.1
20	1.89	150	3.3	1.95	>150	2.4
30	1.91	≥150	3.5	1.98	>150	2.4
40	1.99	≥150	3.2	2.08	≥150	2.2
50	2.01	150	3.2	2.16	≥150	1.6
60	2.04	150	3.2	2.25	≥150	1.4
70	2.03	≥150	4.5	-	-	-

* 1:1:6 GP reference mortar

The results in Table-3, for the 1:0:5 mortars with methyl cellulose additive, revealed a similar trend to those for the 1:1:6 batch. It should be noted that the air content for the 1:0:5 reference mortar was nearly double that of the 1:1:6 mortar. The additional air content is likely to be the reason why adequate workability of these 1:0:5 mortars was achieved at lower flows than the 1:1:6 mortars. For the 1:0:5 mortars, with GGBS or FA, adequate workabilities were achieved at flows around 130±10% compared to a flow value of 100% for the reference mortar. The air content of the 1:0:5 mortars with the GGBS were in the interval between 13 and 15% and for the FA mortars from 10 to 15%. The air content was not observed to decrease with increasing amounts of cement replacement material.

Table-3: Fresh properties of the 1:0:5 mortars.

Replacement of cement [% by volume]	Replacement by GGBS			Replacement by fly ash		
	Water/Binder ratio	Flow [%]	% Air content	Water/Binder ratio	Flow [%]	% Air content
0*	1.32	100	13.3	1.32	100	13.3
10	1.39	130	14.1	1.33	120	15.4
20	1.39	120	13.7	1.46	130	12.2
30	1.40	120	15.0	1.51	135	12.7
40	1.43	135	15.0	1.60	120	10.4
50	1.50	140	12.6	1.61	125	10.6
60	1.51	135	14.0	1.67	120	10.1
70	1.54	135	13.6	-	-	-

* 1:0:5 GP reference mortar

3.2. Flexural bond strengths

3.2.1. 1:1:6 mortars

The flexural bond strengths and coefficients of variation obtained from the masonry prisms prepared with the 1:1:6 mortars incorporating GGBS and FA are given in Table-4 and Table-5 and presented in Figure-1 and Figure-2, respectively.

Table-4: Mean flexural bond strengths - 1:1:6 mortar, GGBS as cement replacement.

Replacement of cement by GGBS [% by volume]	Extruded bricks				Dry pressed bricks			
	7 day strength [MPa]	*7 day COV [%]*	28 day strength [MPa]	*28day COV [%]*	7 day strength [MPa]	*7 day COV [%]*	28 day strength [MPa]	*28day COV [%]*
0	0.95	19.5	1.18	17.2	0.98	13.6	1.21	13.8
10	0.77	13.8	1.09	20.7	0.83	18.3	1.33	21.4
20	0.87	13.7	1.20	28.9	1.19	21.2	1.20	16.6
30	0.68	13.9	1.05	13.3	0.80	28.3	1.11	17.0
40	0.76	15.7	0.92	30.0	0.70	50.5	1.18	29.3
50	0.73	16.9	1.04	30.0	0.72	23.9	1.20	18.5
60	0.68	12.7	1.06	16.1	0.62	22.3	0.99	14.8
70	0.46	11.9	0.91	13.1	0.49	24.9	0.73	30.7

The results in Tables-4 and 5 show that at 7 days for the 1:1:6 mortars, there is an initial gain in bond strength at low levels of replacement with GGBS or FA. Whilst the flexural strength did not continuously decrease with increasing content of cement

replacement material, the overall trend did generally show a reduction in strength. When GGBS was used as cement replacement material, the flexural strength was similar for both unit types with the dry pressed combination producing slightly higher values. Note the increase in bond strength for all mortars between 7 and 28 days.

Table-5: Mean flexural bond strengths - 1:1:6 mortar, FA as cement replacement.

Replacement of cement by FA [% by volume]	Extruded bricks				Dry pressed bricks			
	7 day strength [MPa]	*7 day COV [%]*	28 day strength [MPa]	*28day COV [%]*	7 day strength [MPa]	*7 day COV [%]*	28 day strength [MPa]	*28day COV [%]*
0	0.95	19.5	1.19	17.2	0.98	13.6	1.21	13.8
10	0.73	5.1	1.20	21.5	0.95	21.7	1.32	26.6
20	0.82	12.4	1.25	22.1	0.58	60.6	0.90	41.2
30	0.71	16.3	0.92	20.7	0.56	39.7	0.79	25.8
40	0.81	20.0	1.03	18.7	0.66	25.2	0.81	29.4
50	0.68	17.9	0.93	34.8	0.53	25.0	0.84	19.6
60	0.50	21.4	0.99	22.6	0.40	20.4	0.73	15.0

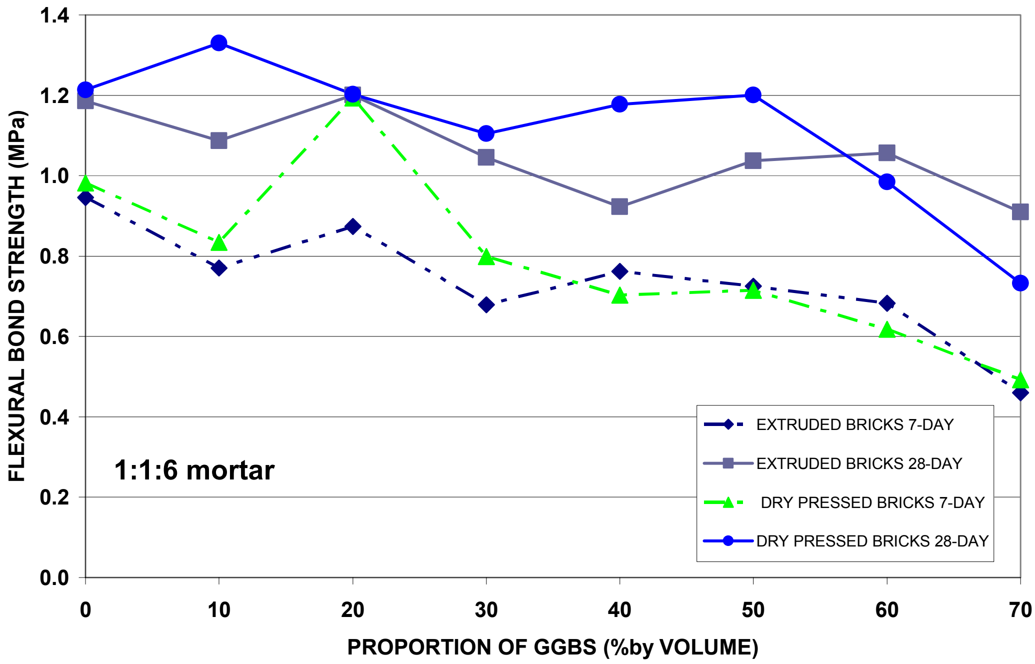

Figure-1. Flexural strengths of masonry prisms, 1:1:6 mortar incorporating GGBS.

The 1:1:6 mortars using FA, as cement replacement material, produced similar bond strengths at 7 and 28 days to the GGBS mortars. Maximum strengths being observed at 28 days with 10% to 20% FA the dry pressed and extruded units respectively. These combinations produced strengths that exceeded the reference mortar strength. With the exception of the 10% FA mix, higher strengths were developed by the extruded units. The coefficient of variation (COV) is generally in the range of 13% to 30% which is typical of that observed with bond wrench testing. The dry pressed unit combinations were an exception and showed higher COV, with the 40% GGBS replacement showing a COV in the order of 50% for 28 day test and the 20% FA blend developing COV of 60% at 7 and 41% at 28 days.

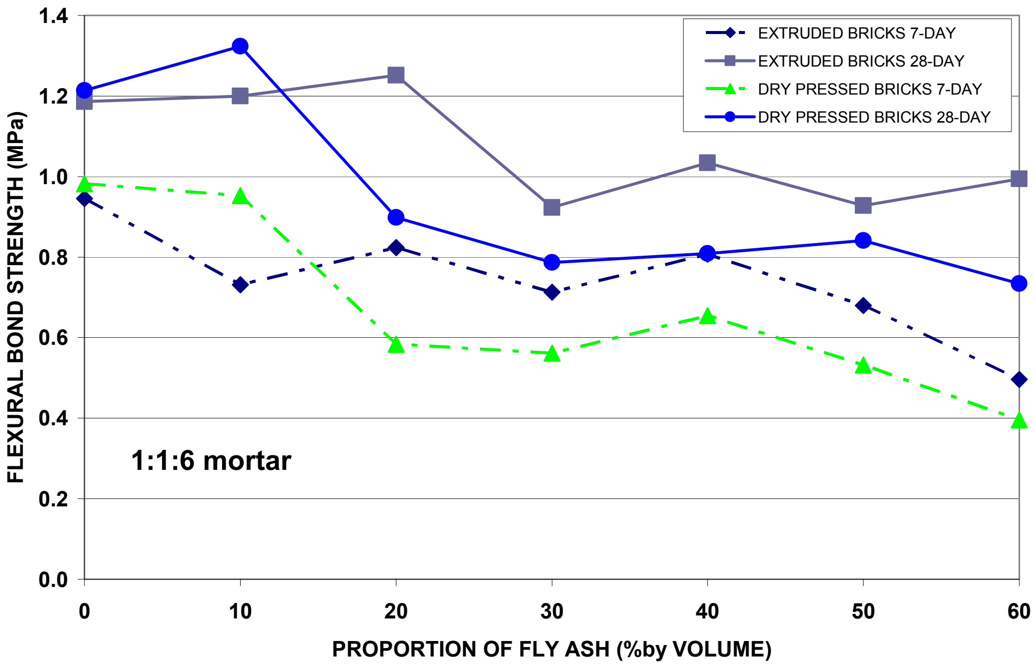

Figure-2. Flexural strengths of masonry prisms, 1:1:6 mortar incorporating FA.

3.2.2. 1:0:5 mortars

The flexural bond strengths with coefficients of variation obtained on masonry prisms prepared with the 1:0:5 mortars incorporating GGBS and FA are given in the Table-6 and Table-7 and presented on the Figure-3 and Figure-4, respectively.

Table-6: Mean flexural bond strengths - 1:0:5 mortar with GGBS.

Replacement of cement by GGBS [% by volume]	Extruded bricks				Dry pressed bricks			
	7 day strength [MPa]	*7 day COV [%]*	28 day strength [MPa]	*28day COV [%]*	7 day strength [MPa]	*7 day COV [%]*	28 day strength [MPa]	*28day COV [%]*
0	0.83	10.7	1.00	9.7	0.94	8.4	1.08	13.5
10	0.63	15.8	0.87	16.5	0.93	20.6	1.14	13.4
20	0.68	7.6	0.93	15.4	0.81	14.1	0.95	25.8
30	0.69	7.7	0.92	12.1	0.84	18.3	1.14	11.2
40	0.62	16.1	0.85	16.1	0.74	41.2	0.97	14.3
50	0.52	12.1	0.84	19.4	0.71	18.2	0.80	21.7
60	0.45	17.2	0.88	10.2	0.68	15.2	1.03	15.5
70	0.48	22.0	0.76	22.1	0.57	12.1	0.73	24.0

The results shown in Tables-6 and 7 indicate similar trends to those observed for the 1:1:6 mortars although the bond strengths for the 1:0:5 mortars were lower. For the 1:0:5 mortars, the reference GP mortar developed higher flexural strength at 7 days than those containing GGBS or FA as cement replacement material. In a similar manner to the 1:1:6 mortars, the flexural strength of the 1:0:5 mortars did not continuously decrease with increasing cement replacement material, but the overall trend was however, decreasing.

Table-7: Mean flexural bond strengths - 1:0:5 mortar with FA.

Replacement of cement by FA [$\%_{vol}$]	Extruded bricks				Dry pressed bricks			
	7 day strength [MPa]	*7 day COV [%]*	28 day strength [MPa]	*28day COV [%]*	7 day strength [MPa]	*7 day COV [%]*	28 day strength [MPa]	*28day COV [%]*
0	0.83	10.7	1.00	9.7	0.94	8.4	1.08	13.5
10	0.74	15.8	0.97	14.0	0.80	16.9	0.92	22.3
20	0.83	16.5	0.99	9.2	0.64	31.0	0.84	20.1
30	0.73	12.1	1.03	22.9	0.62	21.6	0.82	16.8
40	0.50	19.8	0.72	21.6	0.63	19.0	0.70	19.4
50	0.56	16.3	0.84	20.0	0.54	22.6	0.65	22.2
60	0.37	35.0	0.66	27.8	0.35	42.5	0.45	51.3

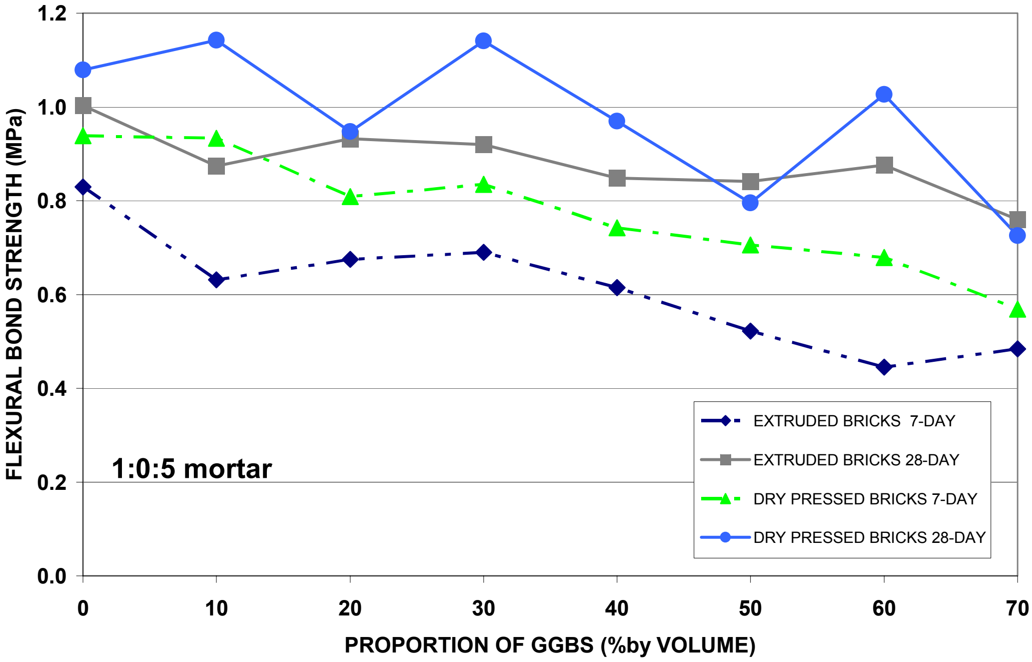

Figure-3. Flexural strengths of masonry prisms, 1:0:5 mortar incorporating GGBS.

When GGBS was used as a cement replacement material, the flexural strength was higher for the pressed bricks than for the extruded bricks for most mixes. For the dry pressed/GGBS combinations, it was observed that at 28 days the 10%, 30% and 60% GGBS replacement developed higher or similar strengths to the reference mortar. For the extruded units, the maximum 28 day strength for the blends occurred at 20% GGBS replacement but this strength did not exceed that of the reference mortar. When FA was used as cement replacement material, the highest strength was obtained with 30% FA content at 28 days. For the dry pressed units, bond strength decreased with increasing FA content for both ages. These trends can be observed in Figures 3 and 4.

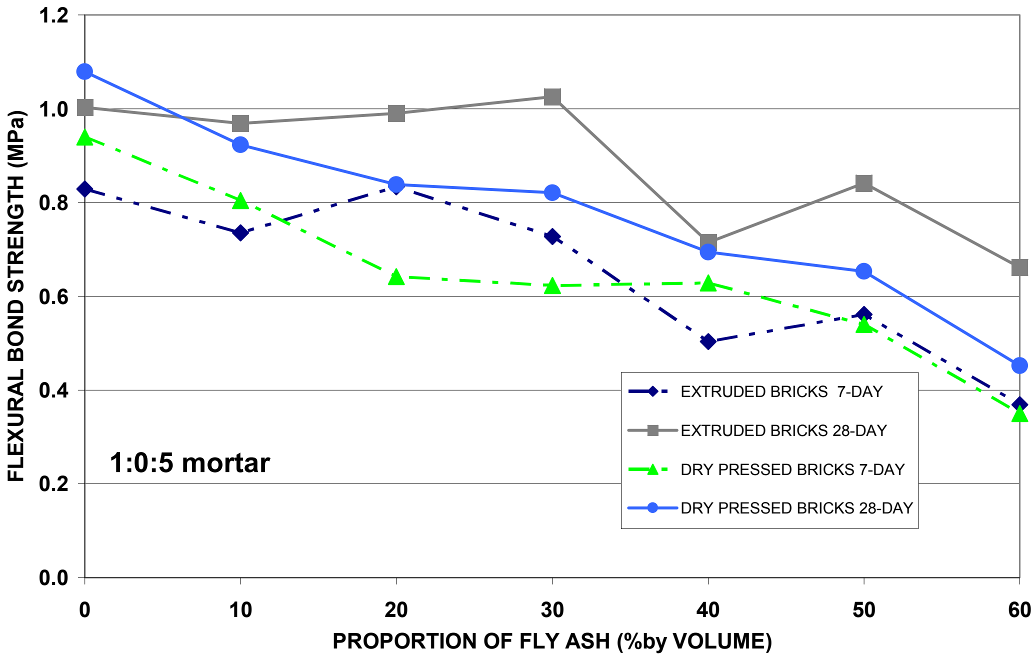

Figure-4. Flexural strengths of masonry prisms, 1:0:5 mortar incorporating FA.

3.3. Tests on Cement Blends

The results of standard consistency, initial and final set and, compressive strength tests on the GP, 70% GGBS and 60% FA (upper limit) blends are summarised in Table-8. It can be observed that the proportion of water required to give a standard consistency increased for both blends. This is likely to reflect the finer particle size and/or greater surface area of these materials relative to the GP cement. The results of initial and final setting times showed that the replacement of cement by 70% of GGBS increased the initial set by nearly two hours whilst the replacement with 60% of FA delayed the initial set by 35 minutes. The difference between initial and final set remained relatively unchanged, with only small increases for the GGBS and FA blends. The reduction in compressive strength is less noticeable for the laboratory blends at 28 days. For the combination of materials used, both blends meet the criteria specified in AS3972, for a general purpose blended cement (Standard Australia, 1997).

Table-8: Properties of GP Cement and Derived Blends.

Cementitious Blend (by volume)	Standard Consistency [%]	Initial Setting Time [Hours]	Final Setting Time [Hours]	Compressive Strength [MPa] 7 day	Compressive Strength [MPa] 28 day
GP cement	27.4	2:20	3:40	42.6	53.1
70% GGBS + 30% GP	34.9	4:10	5:50	21.4	41.4
60% FA + 40% GP	32.3	2:55	4:30	23.4	44.0

4 Discussion

4.1. Fresh mortar properties

From the results presented in Tables-2 and 3 it can be observed that the use of GGBS or FA as cement replacement materials increases the mix water requirements of the fresh mortars. This is likely to be due to a combination of factors. Firstly, these

materials have a lower bulk density and since the mortar is batched on a volume basis the net amount of cementitious material (and fines) in the mortar batch is therefore decreased. This effect is exacerbated by the lack of fines in the sand grading; as a result, the mason is forced to increase the water content of the batch to obtain a workable mix. The second factor relates to the characteristics of the GGBS and FA materials as shown by the standard consistency tests which indicate a greater water demand due to a finer particle size distribution and/or greater surface area. The increase in initial setting time of the GGBS blend, noted in Table-8, would prolong the period of adequate workability in masonry mortars and may therefore be an advantage in hot weather climates.

The use of GGBS and FA decreased slightly the air content in the 1:1:6 mortars. Again, this is likely to be related to the finer particle size of these materials giving rise to suppression of air entrapment and possible interparticle packing. The air content of the 1:0:5 mortars was influenced by the methyl cellulose additive which also has a minor air entrapment role. This has been noted in previous use of this additive (Sugo et al, 1998). The additional air content allowed the 1:0:5 mortars to become workable at lower flows.

4.2. Flexural bond strengths

The observed trends developed by the different mortars and masonry units combination can be observed in Figures 1 to 4.The 1:1:6 mortars with either GGBS or FA materials developed similar bond strengths and bond strength relationships with increasing amount of cement replacement materials. This relationship essentially shows a somewhat lower 7 day strength when compared to the 1:1:6 reference mortar and a gain in strength with age where the developing bond strength equals or exceeds that of the reference GP mortar for low to moderate levels (10% to 30%) of cement replacement material. This maximum is variable depending on the mortar/unit/blend combination as shown in Figures 1 and 2. This observation is consistent with previous studies of the influence of fly ash on masonry bond strength (Reda and Shrive, 2000). At higher levels of cement replacement material >50%, lower levels of bond are observed but these values are still very high >0.7MPa. The reduction in bond at these higher levels of replacement warrants further work, as the relative reduction in bond strength may not be related to the nature of the binder phase but to the amount of binder present in the mortar batch. This effect, as mentioned previously, is related to the lower bulk density of the GGBS and FA, and the volume based batching process used for masonry mortars. The relatively reduction in binder content is in the order of 10-15% for the mortars with high levels of cement replacement materials. If the binder content for these mortars was increased accordingly and improvement in bond strength (and workability) is likely to be observed.

The relationship for the 1:0:5 mortars (with methyl cellulose water thickener) are shown in Figures 3 and 4. Again, there is a gain in strength with age and lower bond strengths are observed at high levels of cement replacement materials, in this case in the 40%-50% replacement. However, bond strength values which equal or exceed the reference mortar values can be observed at several proportions of cement replacement materials. This again implies that the trend is not clear and that very good levels of bond can be achieved even at high levels of GP replacement. In a similar manner to the 1:1:6 mortars, an improvement in bond strength would be expected if the reduction in binder proportions due to lower bulk densities was corrected. A comparison of strengths obtained between the two mortar types would indicate that higher strengths are developed with a 1:1:6 mortar than with a 1:0:5. The contribution of hydrated lime

to masonry bond strength is well known and is related to increasing water retentivity and contributing to the volume of paste in the mortar (Sugo et al, 2001).

There was a large spread of coefficients of variations in the results, ranging from 5% to 51%. These values tended to be larger with the blended mortars. The increase in scatter is likely to be due to the inefficient filling of the bed joints as a result workability difficulties with the fresh mortar. These discontinuities would act as stress concentrations or weakness points and reduce the observed bond strength (Pluijm, 1992).

5 Conclusions

This study has shown that following an initial increase in masonry bond strength, a general reduction in bond strength occurred when high levels of cement replacement materials were used in the mortar. This trend was more noticeable at early ages. The results however are encouraging and indicate that the use of these materials, in high amounts, may be possible if the plastic mortar properties are improved. The lower bulk density of these cement replacement materials results in a reduction of the cementitious content in the mortar, due to the volume batching process, is also likely to be a contributing factor to the lower bond strengths. The high variability of some of the bond strength data limits any firm conclusions to be drawn. Further work is required to investigate both the strength and durability effects of cement replacement materials when used in masonry applications.

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