THE USE OF POZZOLANS TO IMPROVE BOND AND BOND STRENGTH

M. M. Reda Taha[1] and N. G. Shrive[2]

ABSTRACT

Poor bond and low bond strength is a major weakness of brickwork. This bond is affected by many interrelated factors associated with both masonry units and mortar. Lime (CH) is present in masonry mortar as a by-product of cement hydration, particularly at the mortar-unit interface where it produces a weak layer. Hence, we introduced varying amounts and types of pozzolans (fly ash types F and C, and slag) which can react with the lime to produce strong calcium silicate hydrates. The intent was to enhance the bond strength of the masonry by altering the microstructure of the mortar-unit interface. An experimental programme examining the bond strength of mortar-unit joints was therefore carried out, using mortars with and without pozzolans. Statistically significant increases in bond strength were measured at 28, 90 and 180 days with 20% substitution of fly ash in the cementitious materials. No increases were observed with slag. Introducing pozzolans as a mineral admixture in masonry mortar, besides being an environmentally positive feature, can therefore be beneficial from the rheological, economic and structural points of view.

Key words: Masonry bond, Bond dtrength, Pozzolans, Pozzolonic reaction and Water retentivity.

[1.] Ph.D., Structural Engineer, Stantec Consulting Ltd., Calgary, Canada, (mreda@cadvision.com)   (For correspondence)
[2.] Killam Memorial Professor, Department of Civil Engineering, The University of Calgary, Calgary, Canada, (shrive@ucalgary.ca)

BACKGROUND

With the increased interest in performance criteria of construction materials, achieving good bond and acceptable bond strength in masonry has become an essential requirement. This is because mortar-unit joints commonly act as planes of weakness that affect masonry strength, serviceability and durability significantly. Numerous studies over the last four decades have contributed to our outstanding of the mechanism of bond development and its governing factors (e.g. Kampf 1963, Grandet 1973, Chase 1984, Lawrence and Page 1994, Sugo et al. 1997, Groot 1997 and Lange et al. 1999). It is widely accepted that masonry bond incorporates two bond mechanisms. These are chemical bond where covalent or Van der Waals bonds constitute the bond strength between the masonry unit and the cement hydrates; and mechanical bond which is formed by mechanical interlocking of hydration products transferred to the surface pores of the unit. Kampf (1963) showed that the bond strengths between mortar and glass plates are about one tenth of the bond strengths between a similar mortar and masonry brick units. He consequently concluded that mechanical bond contribution to the bond strength is much larger than the chemical one. Dubovoy et al. (1990) confirmed the role of the mechanical bond by proving that rough surface texture of masonry units' results in high bond strength.

Factors affecting bond strength

Bond strength is dependent on many interrelated factors that can directly affect bond development (e.g. unit surface absorption, pore structure, mortar composition, mortar water retentivity and curing conditions) or indirectly affect bond strength (e.g. unit surface texture and workmanship). It was also suggested that both mortar quality and surface absorption criteria of the masonry unit are the most significant parameters in developing good bond and bond strength (Goodwin and West 1982 and McGinley 1990). While the surface absorption characteristics define the rate and volume of water to move from the mortar to the unit, the quality of the mortar defines the amount of water available at the interface and the strength of hydration products deposited in the unit surface pores. The required quality is not necessarily represented by the mortar compressive strength but by other mortar criteria that may indeed be reduced in high strength mortars. Such criteria include mortar workability, water retentivity and plasticity. The interaction of the unit surface absorption and the mortar quality determines the efficiency of the two physical processes that control bond development at the unit interface; densification and dewatering (Groot 1997 and Lange et al. 1999). Densification represents the consolidation of the hydration products at the mortar-unit interface, while dewatering represents the reduction of the water available to complete the hydration process at the interface as a result of unit suction. The limited degree of hydration observed for most hydration products at the mortar-unit interface compared with the mortar core favours this explanation (Goodwin and West 1982). Optimization between water demand and water availability at the mortar-unit interface can improve bond development of at unit interface (McGinley 1990 and Reda Taha et al. 2001).

Microstructure of the interface

Research work on concrete materials revealed the main characteristics of the interfacial region that lies in the vicinity of the aggregate particles in both concrete and mortar

(Mehta 1986, Scrivener 1989 and Larbi 1993). The interfacial region is distinguished by two parts: the duplex film and the transition zone (TZ). The duplex film is layer about 1 μm in thickness directly next to the aggregate, rich in Calcium Hydroxide (CH). Barnes et al. (1978) attributed the formation of the duplex film to the tendency of the calcium silicate hydrates (CSH) to be nucleated above the CH surfaces. The TZ thickness is about 50-200 μm in concrete (Mehta 1986 and Larbi 1993). Smaller TZ have been observed in the immediate vicinity of the masonry unit with an average thickness of 50 μm. The reduction of the TZ size at the masonry interface compared to a concrete aggregate interface with similar water/cement ratio is due to water suction of the masonry unit (Lange et al. 1999).

Energy analysis of the TZ showed that the thermodynamic conditions of the aggregate surface would favour the growth of CH crystals on the aggregate surface rather than at the bulk paste (Larbi 1993). Considering the weak CH crystals, the wall effect and the microbleeding identified by Scrivener (1989) and Larbi (1993), the TZ is characterized by very weak strength, high porosity and multiple microcracking. The wall effect in concrete describes the loose packing of the paste particles at the aggregate surface due to the size difference between the two components. Baché (1981) and Scrivener and Bratt (1996) showed that the wall effect is a function of the size ratio between the two adjacent particles. Baché (1981) concluded that it is impossible practically to eliminate the wall effect of a binary mix if the size ratio is less than twenty. While microbleeding is limited at the masonry interface due to the scarcity of water as a result of the dewatering process, Lange et al. (1999) observed a zone thicker than 50 μm at the unit interface that is free of sand particles. This confirmed that the wall effect at the mortar-unit interface is much larger than that between the aggregate particles and the cement paste. Fig. 1 shows a schematic diagram illustrating the wall effect of mortar particles loosely packed at the flat surface of the masonry unit. It is worthy mentioning that Lange et al. (1999) showed that surface roughness of the masonry unit can counteract the wall effect at the unit interface.
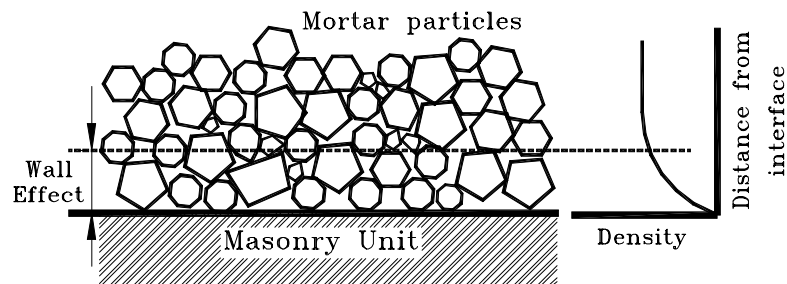

Figure 1. Wall effect in the immediate vicinity of masonry unit (Baché 1981)

Microstructural investigations revealed that mortar-unit interface is rich in tri-calcium-sulpho- aluminate ($3CaO.Al_2O_3.3CaSO_4.32H_2O$) known as "Ettringite" and CH crystals (Lawrence and Cao 1988, Reda and Shrive 2000 and Sugo 2001). Ettringite is in the shape of hexagonal needle-like crystals and is formed during early stages of cement hydration from reaction between C_3A and gypsum. As hydration progresses, ettringite is usually converted to Monosulphoaluminate which is more stable than ettringite (Mehta

1986). The existence of ettringite at later ages has been attributed to the absence of enough water for the hydration process to continue as a result of unit suction (Lawrence and Cao 1988).

There have been differing observations regarding the existence and role of CH crystals at the mortar-unit interface. Lange et al. (1996 and 1999) observed very few CH crystals at the mortar-unit interface and reported the contribution of CH to bond strength to be non-significant. On the other hnad, Lawrence and Cao (1988), Sugo et al. (1997), Reda and Shrive (2000) and Sugo (2001) proved using XRDA analysis and SEM investigations that there is considerable CH in the interface and the quantity is substantially increased when lime is included in the mix. Coarse CH crystals were also observed when saturated clay units were used. Chase (1984), Lawrence and Cao (1987) and McGinley (1990) attributed the mechanical bond mainly to a wide interwoven fibrous network of C-S-H growing at the unit surface. Reda and Shrive (2000) showed that a strong CSH fibrous network can significantly enhance masonry bond when fly ash is incorporated in the mortar mix. Sugo (2001) suggested the use of silica fume to enhance masonry bond strength but no experimental work supported this proposal. The high reactivity of silica fume may not make it the most suitable pozzolanic admixture for masonry mortar because its fast rate of hydration would be expected to reduce mortar water retentivity. However, the use of other pozzolans such as fly ash or slag might effectively enhance the interface bond strength.

Pozzolanic Materials

While fly ash is typically precipitated electrostatically in coal-fired power stations, blast-furnace "slag" is a waste by-product from the production of pig iron. Therefore, utilization of fly ash and/or slag in the construction industry, besides being of strength and durability benefit, has environmentally positive features. Fly ash and slag are also cheap compared to Portland cement. While slag has been used for more than 100 years, fly ash is of relatively recent origin (Mehta 1986). The Canadian standards (CSA A23.5M-86, 1986) and the American standards (ASTM 618-95, 1995) recognize two types of fly ash: class C originating from subbituminous coal origin and class F from bituminous coal. The main difference between class C and class F fly ash is that class C has a higher calcium content than class F. Many references identify class C and class F as high and low calcium fly ash respectively. In spite of the benefit of classifying fly ash especially for ensuring consistent performance, Aïtcin et al. (1986) showed that it is difficult practically to fit any fly ash within a specific category. Therefore, the choice of a fly ash type for a specific application should be based on performance criteria rather than fixed clasification. Detailed reviews on fly ash and slag and their properties are provided elsewhere (Malhotra and Ramezanianpour 1994 and Hooton 2000).

Fly ash was investigated as early as 1937 for use in concrete to enhance its mechanical performance (Davis 1937). Both fly ash and slag were reported to enhance the properties of fresh and hardened concrete with confirmed contribution to long-term strength and durability. However, the effect of pozzolans on the bond and bond strength of masonry has rarely been investigated (Reda and Shrive 2000). The effect of fly ash or slag on hardened concrete is attributed to its pozzolanic activity, by which the pozzolans chemically convert the weak CH crystals to strong CSH fibrous gel. The pozzolanic activity depends mainly on the chemical composition and the fineness of the pozzolans. The pozzolanic reaction of fly ash was reported to have a significant effect on strength development when long-term strength rather than short-term strength is of concern. Therefore, the characteristic 28-day mortar strength does not necessarily reflect the long-

term behaviour of fly ash mortar because of the long time period required for the pozzolanic reaction to be completed.

EXPERIMENTAL PROGRAMME

Materials

We therefore examined the effect of pozzolans on interface bond and bond strength. The materials used in this work included two types of cement: Type 10 Portland cement (ordinary Portland cement) in accordance with CSA A5-93 (1993), and slag blended cement complying with the Canadian specifications for blended cements (CAN-A362, 1998). The hydrated lime was in conformance with ASTM C821-78 (1984). Two types of fly ash were also incorporated; class F and class C complying with ASTM C 618-95 (1995). All specimens were built using extruded clay bricks 90 mm x 190 mm in cross section with 10 cores of 20 mm diameter each. The mean and standard deviation of the basic properties of 10 of these brick units (ASTM C67-86, 1986) are given in Table 1. The pozzolans were used as a partial replacement of either the cement or the cement and the lime in type N mortar. The relative mix proportions of the four mortar mixes examined here are presented in Table 2.

Table 1. Basic characteristics of brick units

Property	ρ (kg/m^3)	IRA (m/cm^2/minute)	Absorption (%)	σ_1 (N/mm^2)
Average	938.9	21.7	7.6	47.3
Std. Dev.	4.5	5.2	0.3	3.9

Table 2. Mix Proportions of the mortar groups examined

Mortar group	Portland Cement	Slag Cement	Hydrated lime	Fly ash Type (F)	Fly ash Type (C)	Sand
N	1	---	1	---	---	6
FF	0.8	---	0.8	0.4	---	6
CF	0.8	---	0.8	---	0.4	6
SL	---	1	1	---	---	6

The levels of pozzolans replacement used here is based on work examining the effect of type F fly ash on the interface bond strength (Reda and Shrive 2000). The highest bond strength was attained at 180 days with 20 percent of the total cementitious materials replaced by fly ash by volume (i.e. 20 percent of the lime plus 20 percent of the Portland cement). To examine the effect of slag cement; Type 10 Portland cement was replaced by slag-cement. No replacement of lime was incorporated in this mix.

Fifteen five-high stack bonded prisms were made with each mortar type. All prisms were moist cured by leaving them in a fog room at 20 ^{o}C and 100 percent RH. The use of moist curing was also reported to provide more consistent results than dry curing when pozzolans are incorporated in the mortar mix (Reda and Shrive 2000). Masonry prisms were tested at 28 days, 90 days, 180 days of age.

Bond Wrench Test

Several methods have been proposed over the last two decades for examining the flexural bond strength of mortar-unit interface (Goodwin and West 1982, ASTM C1072-94 (1994), and Samarasinghe et al. 1999). The bond wrench test apparatus described here was developed by Shrive and Tilleman (1992) for examining flexural bond strength of masonry prisms. The test procedure complies with the basic requirements of ASTM C1072-94 (1994). The top half of the brick is gripped between two neoprene pads in a clamp and a torque wrench is then attached to the clamp such that the centre-line of the torque wrench arm is centred on the brick. The test apparatus was calibrated and the tensile flexural bond strength is calculated using equation (1).

$$\sigma_t = (0.0038457 \, ((1.355818 * T) - 11)) + 0.06 \qquad (1)$$

σ_t is the flexural bond strength in MPa and T is the wrench reading in ft lbs.

Statistical Analysis

Statistical analyses using the analysis of variance (ANOVA) and the t-test were performed to examine the significance of incorporating pozzolans on the mortar-unit interface bond strength. All analyses were performed assuming a level of significance of 5 percent. Data homogeneity was first tested using Bartlett's method, followed by applying the ANOVA test to the compared test results. To compare between pairs of mortars, the t-test using the student-t distribution was applied to each pair of samples. A similar process was used to examine the effect of time on the bond strength of all the mortar mixes examined. The statistical analysis revealed whether the compared groups are significantly different (SD) or non different (ND).

RESULTS AND DISCUSSIONS

All mortars incorporating fly ash showed consistent workability with a pot life in excess of two and half hours as required by the Canadian standard (CSA A179-94, 1999). The mason was allowed to control the water content of all the mixes to provide the required workability similar to the on-site conditions specified by the Canadian standards (CSA A179-94, 1999). However, it was observed that the mason was able to use less water to achieve the desired degree of workability when fly ash (especially class F) was incorporated. This observation is in agreement with the known ability of class F fly ash to enhance the workability of concrete (Naik and Ramme 1990).

The values of interface bond strength of the five prisms tested at each of the three ages (28, 90 and 180 days) for the four different types of mortar are presented in Table 3. Each value in the table represents the mean of four tests on the four mortar layers in each masonry prism. The mean and standard deviation of the five prisms for each mortar type

at each testing age are also shown in Fig. 2 for visual comparison.

Table [3]: Bond strength test results (MPa).

Age (days)	Prism #	Mortar Group			
		N	CF	FF	SL
28 days	Prism 1	0.59	0.52	0.86	0.37
	Prism 2	0.58	0.57	0.74	0.40
	Prism 3	0.86	0.50	0.85	0.49
	Prism 4	0.86	0.54	0.79	0.45
	Prism 5	0.78	0.57	0.82	0.38
	Average	0.72	0.54	0.81	0.42
	Std. Dev.	0.14	0.05	0.05	0.06
90 days	Prism 1	0.72	0.73	1.06	0.46
	Prism 2	0.70	0.75	0.98	0.50
	Prism 3	0.75	0.70	1.13	0.51
	Prism 4	0.80	0.72	0.97	0.60
	Prism 5	0.73	0.68	1.18	0.54
	Average	0.74	0.72	1.06	0.52
	Std. Dev.	0.09	0.12	0.11	0.11
180 days	Prism 1	0.73	0.80	1.19	0.60
	Prism 2	0.64	0.85	1.09	0.45
	Prism 3	0.83	0.82	1.11	0.55
	Prism 4	0.87	0.97	1.22	0.57
	Prism 5	0.87	0.96	1.10	0.61
	Average	0.79	0.88	1.14	0.56
	Std. Dev.	0.15	0.06	0.12	0.09

Bond strength results

Test results generally show an increase of late age bond strength when either class C or class F fly ash was incorporated in the masonry mortar and a general decrease at all ages when the Portland cement was replaced by slag cement. Comparing CF mortar (including class C fly ash) with type N mortar, the bond strength of the CF mortar was lower by 25 percent at 28 days, developed to be approximately equal at 90 days and then showed an increase of 11 percent at 180 days. The bond strength of FF mortar (including class F fly ash) was consistently higher than that of Type N mortar by 12, 43 and 44 percent at 28, 90 and 180 days respectively. On the other hand, SL mortar (including slag cement) showed bond strengths lower than type N mortar by 42, 30 and 29 percent respectively. With the complex mechanism of mortar-unit bond development, the different performance of the pozzolans examined could not be attributed only to the pozzolanic activity of the pozzolans (i.e. converting the weak CH crystals to strong CSH gel). This is because the strength of the hydration products is not the only factor governing the bond

strength of the interface. The effect of the pozzolans on bond strength is governed by a number of interrelated factors including; the ability of the pozzolans to enhance the workability and water retentivity of the mortar mix, the size of the pozzolans particles and their capability to reduce the wall effect between the mortar particles and the unit, and finally the reactivity of the pozzolans. If the pozzolanic material can enhance the mortar workability, the mason will be able to reduce the water needed to achieve a specific workability, thus enhancing the quality of the mortar at the interface. This could explain the observed improvement of the bond strength of mortar type FF including class F fly ash with the observed reduction of water requirement of the fresh mortar mix. With the ability of moderate reactive pozzolans to increase the amount of fine materials in the mortar mix, the water retentivity will be improved. Thus water will remain for a longer time at the interface allowing the hydration process to continue, thus improving the bond strength of the interface.
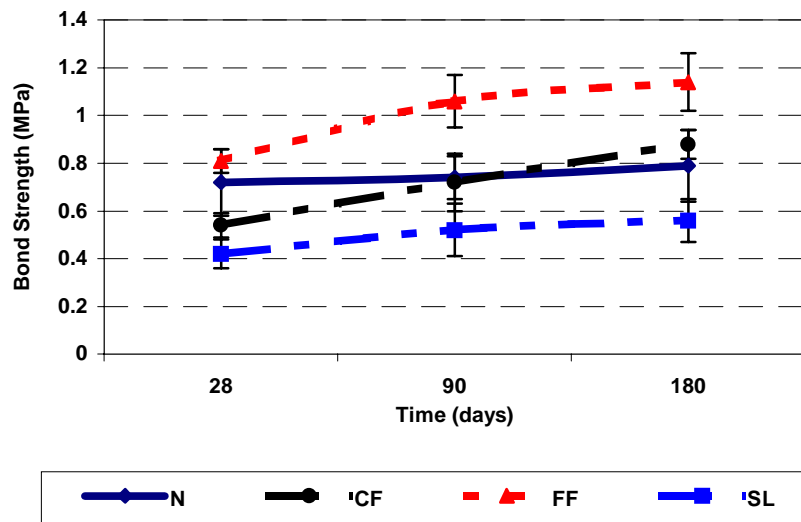

Figure 2. Effect of time on bond development for mortars with and without pozzolans.

It is well established that the fly ash particle size ranges from (1-150 µm) while the Portland cement particle size ranges from (1-50 µm) (Malhotra and Wallace 1993). Therefore, the average particle size of fly ash (75 µm) will be larger than the average Portland cement particle size (25 µm) but smaller than the smallest aggregate particle (150 µm). Thus fly ash would contribute with the existing mortar particles to forming a dense packing particle system that will help reduce the wall effect between the mortar particles at the unit surface. In contrast, the effect of the pozzolans on the wall effect at the interface will be minimal in the case of the slag cement since the particle size of slag is in the same range as that of Portland cement. Finally, the reactivity of the pozzolans affects interface bond development through two counteracting mechanisms; high reactive pozzolans will allow early formation of the CSH gel and these strong hydrates will provide the mechanical interlock between the unit and the mortar enhancing the bond strength. On the other hand, the high reactivity of certain pozzolans could result in fast consumption of water and thus induce early shrinkage cracking at the interface tending to reduce the bond strength. Therefore, an optimum reactivity of the pozzolans would allow

short and long-term formation of the CSH gel in conjunction with providing adequate water retentivity. With the pronounced increase of the bond strength of class F fly ash compared to class C fly ash and the known high reactivity of class C fly ash compared to class F fly ash (Malhotra and Ramezanianpour 1994), class F fly ash appears to have more suitable reactivity for bond strength development. The decrease of bond strength observed in the slag-cement mix, might be due to the decrease in the active binder (Portland cement) content. Other researchers (Goodwin and West 1982 and Reda and Shrive 2000) have reported the need for a minimum limit of active cementing material.

Statistical inference

Results of the statistical tests examining the significance of including pozzolans and the significance of age on bond development and bond strength are presented in Tables 4 and 5 respectively. Statistical testing using ANOVA showed that when fly ash is incorporated there is a significant difference between the compared groups. Further statistical analysis using the student t-test showed that replacing part of the Portland cement and lime by class F fly ash significantly improved bond and bond strength of masonry interface at later testing ages (90 and 180 days). With class C fly ash there were no significant increases in strength, but a significant reduction at 28 days. Replacement with slag cement caused a significant reduction in bond strength at all ages.

Table [4]: Significance of adding pozzolans on the bond strength

Compared groups	28 days	90 days	180 days
CF-N	SD[*]	ND[*]	ND
FF-N	ND	SD	SD
SL-N	SD	SD	SD

*SD (Significantly different), ND (Non-different)

Table [5]: Significance of age on bond strength development

Age (days)	N	CF	FF	SL
90-28	ND[*]	SD[*]	SD	SD
180-28	ND	SD	SD	SD

*SD (Significantly different), ND (Non-different)

Examining the effect of age, when type N mortar was used, no significant changes occurred from 28 to either 90 or 180 days. However, with the pozzolans significant increases in bond strength between 28 to both 90 and 180 days were observed. The significance of age on development of bond and bond strength can be explained by the long time period required for the pozzolanic reaction to be completed.

CONCLUSIONS

- Fly ash can be used in masonry mortar to improve long-term bond strength. Partial replacement of the Portland cement and lime with class F fly ash significantly improved masonry bond strength. Class C fly ash provided limited enhancement to the long-term bond strength. Both materials can provide more cost-effective, high durable, environmentally friendly mortar than mortar without fly ash.
- Incorporation of blended slag cement significantly reduced masonry bond strength.
- The effect of pozzolans on masonry bond strength could not be attributed to the pozzolanc reaction alone. This is because the incorporation of pozzolans affects other factors including the water requirement of fresh mortar, water retenitivity and the wall effect between the mortar particles at the unit interface. While the reactivity of the pozzolans is needed to improve bond strength, the effect of the other factors should not be neglected when selecting the suitable pozzolans for a specific mortar mixture.

REFERENCES

Aïtcin, P. C., Autefage, F., Carles-Gibergues, and Vaquier, A. (1986). Comparative Study of the Cementitious Properties of Different Fly Ashes, ACI SP-91, pp. 91-114.

American Society for Testing and Materials, ASTM C821-78. (1984). Standard Specifications for Lime for Use with Pozzolans, Philadelphia, USA.

American Society for Testing and Materials, ASTM C67-86. (1986). Standard Methods of Sampling and Testing Brick and Structural Clay Tile, Philadelphia, USA, pp. 51-61.

American Society for Testing and Materials, ASTM C1072-94. (1994). Standard Specifications for Standard Test Method for Measurement of Masonry Flexural Bond Strength, Philadelphia, USA.

American Society for Testing and Materials, ASTM C 618-95, (1995). Specification for Fly Ash and Raw or Caclined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete, Philadelphia, USA.

Baché, H.H. (1981). Densified Cement/Ultra-Fine Particle-Based Materials, Second International Conference on Superplasiticzers In Concrete, Ottawa, Canada, 35 p.

Barnes, B. D., Diamond, S. and Dolch, W. L. (1978). The Contact Zone Between Portlans Cement Paste and Glass (Aggregate) Surfaces, Cement and Concrete Research, Vol. 8, pp. 233-244.

Canadian Standards Association, CSA A23.5–M 86, (1986). Supplementary Cementing Materials, CSA/CAN, Rexdale, Ontario, Canada.

Canadian Standards Association, CSA A5-93 (1993). Portland Cement, CSA/CAN, Rexdale, Ontario, Canada.

Canadian Standards Association, CSA A362 (1998). Blended Hydraulic Cement, CSA/CAN, Rexdale, Ontario, Canada.

Canadian Standards Association, CSA A179–94, (1999). Mortar and Grout for Unit Masonry, CSA/CAN, Rexdale, Ontario, Canada, 46 p.

Chase, G.W. (1984). Investigations of the Interface between Brick and Mortar, The Masonry Society Journal, Vol. 3, No. 2, pp. T1-T9.

Davis, R. E., Carlson, R. W., Kelly, J. W. and Davis, H. E. (1937). Properties of Cements and Concretes Containing Fly Ash, Journal of the American Concrete Institute, Vol. 33, pp. 557-612.

Dubovoy, V. S. and Ribar, J. W. (1990). Masonry Cement Mortars- A Laboratory Investigation, Portland Cement Association (PCA) Research and Development Bulletin RD095T. Skokie, USA.

Goodwin, J.F. and West, W.H. (1982). A Review of the Literature on Brick/Mortar Bond, Proceedings of the British Ceramic Society, Vol. 30, No. 23, pp. 23-37.

Grandet, J. (1973). Physico-Chemical Mechanisms of the Bond Between Baked Clay and Cement, Proceedings of the 3rd International Masonry Conference (IMC), Essen, Germany, pp. 217-221.

Groot, C. J.W.P. (1997). The Characteristics of Brick and Mortar Considering Mortar/Brick Bond, Proceedings of the 11th International Brick/Block Masonry Conference, Tongji University, Shanghai, China, pp. 50-58.

Hotoon, R. D. (2000) "Canadian use of ground granulated blast-furnace slag as a supplementary cementing material for enhanced performance of concrete", Canadian Journal of Civil Engineering, Vol. 27, No. 4, pp. 754-760.

Kampf, L. (1963). Factors affecting Bond of Mortar to Brick. Symposium on Masonry Testing, American Society for Testing and Materials, ASTM STP 320, pp. 127-141.

Lange, D.A., Deford, H.D. and Ahmed, A. (1996). Microstructure and Mechanisms of Bond in Masonry, Proceedings of Seventh North American Masonry Conference, University of Notre Dame, South Bend, Indiana, USA, pp. 167-174.

Lange, D. A,m Deford, H. D. and Werner, A. M. (1999). Microstructural Investigation of Mortar/Unit Interaction, Journal of The Masonry Society, pp. 31-42.

Larbi, J. A. (1993). Microstructure of the interfacial zone around aggregate particles in concrete, Heron, Vol. 38, No. 1, 69 p.

Lawrence, S.J. and Cao, H.T. (1988). Microstructure of the Interface Between Brick and Mortar, Proceedings of the 8th International Brick/Block Masonry Conference, Dublin, DeCourcy, J.W., Ed., Vol.1, pp. 194-204.

Lawrence, S.J. and Cao, H.T. (1987). An Experimental Study of the Interface between Brick and Mortar, Proceedings of the 4th American Masonry Conference, Los Angeles, pp. 48/1-48/14.

Lawrence, S.J. and Page, A.W. (1994). Bond Studies in Masonry, Proceedings of the 10th International Brick and Block Masonry Conference, Shrive, N.G., and Huizer, A. Ed., Calgary, Canada, pp. 909-917.

Malhotra, V. M. and Ramezanianpour, A. A., (1994). Fly Ash in Concrete, Second edition, CANMET, 307 p.

Malhotra, V. M. and Wallace, G. G. (1993). A new method for determining fineness of cement, Energy, Mines and Resources Canada, Ottawa, Ontario, Mines Branch Investigation Report 63-119.

McGinley, W.M. (1990). IRA and The Flexural Bond Strength of Clay Brick Masonry, Masonry : Components to assemblages, Matthys, J.H., Ed., American Society for Testing and Materials, ASTM STP 1063, pp. 217-234.

Mehta, P.K. (1986). Concrete, Structure, Properties and Materials, Prentice-Hall, Inc.,

NY., 450 pp.

Naik, T.R. and Ramee, B. W. (1990). Effect of high-lime fly ash content on water demand, time of set, and compressive strength of concrete, ACI Materials Journal, Vol. 87, pp. 619-626.

Reda, M. M. and Shrive N.G. (2000). Enhancing Masonry Bond Using Fly Ash, Masonry International, Journal of the British Masonry Society, Vol. 14, No. 1, pp. 9-17.

Reda Taha, M. M., El-Dieb, A. S. and Shrive, N. G. (2001). Sorptivity: A Reliable Measurement for Surface Absorption of Masonry Brick Units, In Press, Materials and Structures, RILEM, France.

Samarasinghe, W., Lawrence, S.J. and Page, A. W. (1999). Standardizing the Bond Wrench, Proceedings of the 5th Australian Masonry Conference, Gladstone, Queensland, Australia, Page, Dhanasekar, and Lawerence, Ed., pp. 335-344.

Scrivener, K. L. (1989). The Microstructure of Concrete, Materials Science of Concrete, Skalny, I. J., Ed., American Ceramic Society, pp. 127-162.

Scrivener, K. L. and Pratt, P. L. (1996). Characterization of the interfacial microstructure, Interfacial Transition Zone in Concrete, State-of-the-Art-Report prepared by RILEM Technical Committee 108-CC, Interfaces in Cementitious Composites, Maso, J. C., Ed., E&F Spon, London, UK.

Shrive, N.G. and Tillemann, D. (1992). A Simple Apparatus and Method for Measuring On-Site Flexural Bond Strength, Proceedings of the 6th Canadian Masonry Symposium, Saskatoon, pp. 283-294.

Sugo, H. O., Page, A.W. and Lawrence, S.J. (1997). Characterization of Bond Strengths of Mortars with Clay Masonry Units, Proceedings of the 11th International Brick/Block Masonry Conference, Tongji University, Shanghai, China, pp. 59-68.

Sugo, H. O. (2001). Strength and Microstructural Characteristics of Brick/Mortar Bond, Ph.D. Dissertation, Department of Civil, Surveying and Environmental Engineering, The University of Newcastle, Newcastle, Australia.