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Industrial By-Products for Sustainable Concrete Structures

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ABSTRACT

Certain industrial by-products possess pozzolanic properties. Replacement of portland cement by one or more of such products is already practiced. This practice has been more often applied within the usual processes of concrete production. Unawareness of, or ignoring certain particularities of the by-product may result in inefficient utilisation and may lead to undesirable outcomes. Identifying such particularities and their effects on the processes of manufacturing concrete as well as its durability is necessary. Such identification serves to draw strategies for optimised usage of industrial by-products. It also leads to minimising the use of ordinary portland cement, prolong the service life of concrete structures and make full use of otherwise waste and polluting materials. This paper advocates a revised attitude towards certain practices in concrete production. It also draws attention to the importance of 'engineering' the by-products for the specific purposes and circumstances of service for which concrete structures are designed.

INTRODUCTION

Concrete is the most used man made material of modern times [Lomborg, 2001]. The average of concrete consumption is 1 m^3 per person on Earth [Aitcin, 2000]. Estimates of the amount of CO_2 that results from the manufacture of cement vary from 0.8 to 1.0 tonne of CO_2 per tonne of cement produced [Gartner, 2004; Huntzinger & Eatmon, 2009]. Recent studies estimate that the cement industry contributes 5-8% of the total CO_2 emissions [Huntzinger & Eatmon, 2009; Mora, 2007; Scrivener & Kirkpatrick, 2008]. Any reduction in this undesirable contribution should be encouraged.

Without going into great detail, it is easy to argue that protecting construction from deterioration is a major key to avoid repair or reconstruction that, in turn, need additional cement. Thus, durability of concrete is necessary for sustainability.

The benefits of including industrial by-products in concrete have been explored for many years [Kayali, 2008; Kayyali & Haque, 1988; Meyer, 2009]. The advantages derived from such inclusion render these products to be considered necessary ingredients of concrete rather than just a way of reducing cost with inert fillers [Ahmaruzzaman; Kayali & Zhu, 2005; Sukumar, Nagamani & Srinivasa Raghavan, 2008].

As there is an existing trend towards producing high and ultra-high strength concrete, the inclusion of silica fume has become quite common in order to make such concretes. Inevitably, circumstances where silica fume is included in concretes that already contain GGBFS and/or fly ash will occur. The durability aspects of such blends have not been adequately researched [Ganjian & Pouya, 2009].

In this paper, the authors present aspects of the performance of concrete that was made with a combination of cementitious industrial by-products. Particularities of such concretes are drawn to attention in view of their implication on the manufacturing stage and thus the long-term performance. For this purpose, two series of concretes were manufactured. One with various combinations of cement, fly ash, silica fume and blastfurnace slag, while the second series concentrated on particularities of metakaolin-cement blends.

MATERIALS AND TESTING

Cementitious Materials Blends. In the series devoted for examining the blends of fly ash,silica fume, GGBFS and OPC, crushed, washed and oven dried coarse aggregates of 9.5 mm maximum size, were used. Washed river bed sand was used as fine aggregates. Concrete mixes were cast with total cementitious materials content of 450 kg/m^3. The water to binder ratio in all mixes of this series was 0.38. The OPC was replaced with low, medium, and high percentage of fly ash or GGBFS at the replacement levels of 25, 50, and 70%. Silica fume was used at 10% replacement of the total cementitious materials content in all the ternary mixes. The chemical analysis of OPC, fly ash, silica fume, and GGBFS used in this series is shown in Table 1.

Table 1. Chemical composition of the OPC cement, SF, FA and BFS

Chemical composition	Cement %	SF %	FA %	BFS %
SiO_2	21.1	>90	67.5	34.1
Al_2O_3	5.2	<0.9	23	13.2
Fe_2O_3	4.3	<1.5	4.5	0.7
CaO	64.2	<0.4	<1	41.8
MgO	1.2	<0.1	<1	6.3
Na_2O, K_2O	0.05, 0.47	<0.4, <0.9	0.5, 1.5	0.27,0.34
SO_3	2.6%	<0.03	0.1	2.4
L on Ignition	0.8%	-------	1.0	-0.5
Specific Gravity	3.13	2.24	2.13	2.86
Fineness Index (m^2/kg)	350	23, 500	310	425

The mixes in this series are designated as follows: The letters OPC, S, F, and B stand for ordinary portland cement, silica fume, fly ash, and blast furnace slag blends, respectively. For example, in the mix B7S1, B7 represents 70% replacement of cement by blast furnace slag, and S1 represents 10% replacement of cement with silica fume. In the mix F2S1, F2 represents 25% replacement of cement by fly ash, and S1 represents 10% replacement of cement with silica fume. In the mix B2, B2 represents 25% replacement of cement with BFS, and in the mix B5, B5 represents 50% replacement of cement with BFS. The mix OPC is the control mix with 0.38 w/b ratio as well. Details of the mixes and their contents are listed in Tables 2 and 3.

Table 2. Mix Design and Some Fresh and Mature Properties of the Mixes*; W/B: 0.38**

Materials and Properties	OPC	S1	F2	F2S1	F5	F5S1	F7	F7S1
Cement (kg/m^3)	450	405	337.5	292.5	225	180	135	90
Silica fume (kg/m^3)	-	45	-	45	-	45	-	45
fly ash (kg/m^3)	-	-	112.5	112.5	225	225	315	315
Total cementitious content (kg/m^3)	450	450	450	450	450	450	450	450
Coarse Aggregate (kg/m^3) -	1110	1101	1083	1074	1056	1046	1034	1025
(oven Dried)								
Fine Aggregate (kg/m^3) -	680	675	664	658	646	642	633	628
(oven Dried)								
Superplasticizer L/100 kg binder	1.14	1.3	1	1	0.6	1	0.8	1
Water-Effective (kg) - (Free)	171	171	171	171	171	171	171	171
Slump (mm)	65	85	130	60	50	50	25	35
Air content (%)	1.65	0.9	1.2	1.5	1.2	1.75	1.35	1.95
Hardened concrete (kg/m^3) at 365 Days	2360	2344	2298	2276	2232	2226	2164	2135
Compressive Strength (MPa) – 365 Days	76.8	73.4	58.8	59.3	37.8	34.5	15.6	11.6

*: Control, silica fume, and fly ash mixes

Table 3. Mix Design and Some Fresh and Mature Properties of Mixes$^+$; W/B: 0.38**

Materials and Properties	OPC	S1	B2	B2S1	B5	B5S1	B7	B7S1
Cement (kg/m^3)	450	405	337.5	292.5	225	180	135	90
Silica fume (kg/m^3)	-	45	-	45	-	45	-	45
Blast furnace slag (kg/m^3)	-	-	112.5	112.5	225	225	315	315
Total cementitious content (kg/m^3)	450	450	450	450	450	450	450	450
Coarse Aggregate (kg/m^3) - (oven Dried)	1110	1101	1105	1096	1100	1091	1111	1102
Fine Aggregate (kg/m^3) – (oven Dried)	680	675	677	672	674	669	681	675
Superplasticizer L/100 kg binder	1.14	1.3	1.3	1.31	1.2	1.3	0.94	1.3
Water-Effective (kg) - (Free)	171	171	171	171	171	171	171	171
Slump (mm)	65	85	200	90	35	130	155	110
Air content (%)	1.65	0.9	0.35	1.4	0.7	1.15	0.75	1.15
Hardened concrete (kg/m^3) at 365 Days	2360	2344	2357	2330	2341	2318	2361	2324
Compressive Strength (MPa) – 365 Days	76.8	73.4	68.5	64.3	55.6	53.2	58.6	56.9

+: Control, silica fume, and blast furnace slag mixes

**:For both Tables 2 and 3: Aggregate quantities are based on oven dry condition, while the water reported is the free water

The first series was subjected to durability testing using the RCPT (Rapid Chloride Permeability Test) as the yard stick for durability. The test was done following the procedures outlined in AASHTO-T277 [1989]. For each mix, 8 disc specimens of 100 mm diameter and 50 mm thickness were cast. The concrete specimens were demoulded 24 hours after casting and were fog cured for a period of 7 days. The test was performed on all the samples of this series after 350 days of exposure in an environmental room maintained at 23^{o}C and 50% RH.

The Metakaolin Series. Concrete mixes consisted of Portland cement (PC), metakaolin (MK), water, fine aggregate that complied with class M of BS 882: 1992, and 20 mm nominal size crushed and washed coarse aggregate. The superplasticiser (SP) used was Naphthalene Sulphonate based liquid. The composition of MK is shown in Table 4.

Table 4. Chemical Composition of the OPC and the Metakaolin Used in Series 2

		OPC	**MK**
SiO_2	%	20.2	52.1
Al_2O_3	%	4.2	41.0
Fe_2O_3	%	2	4.32
CaO	%	63.9	0.07
MgO	%	2.1	0.19
SO_3	%	3	-
Na_2O	%	0.14	0.26
K_2O	%	0.68	0.63
Insoluble Residue	%	0.37	-
Loss on Ignition	%	2.81	0.6
Free Lime	%	2.37	-
Specific Surface Area	m^2/kg	367.8	12,000
Residue Retained on 45 μm Sieve	%	15.16	-
Initial Set	min	115.0	-

Details of the different mixes (M1-M6) used in this study are presented in Table 5. The control mix (M1) had a proportion of 1 (PC): 1.26 (fine aggregate): 2.6 (coarse aggregate) and did not include MK.

Table 5. Details of the Metakaolin Mixes

Mix No.	**MK %**	**OPC**	**MK**	**Water**	**Fine Aggregate**	**Coarse Aggregate**
1	0	482	0	145	608	1254
2	5	474	24	150	629	1298
3	7.5	470	36	153	641	1322
4	12.5	462	60	158	665	1372
5	15	457	72	161	678	1398
6	20	447	96	168	705	1454

In mixes M2-M6, OPC was partially replaced with 5%, 7.5%, 12.5%, 15% and 20% MK (by mass) respectively. The water to binder ratio for all mixes was maintained constant at 0.30.

The dosage of SP was 1.36% by mass of binder for all mixes. Concrete specimens consisted of fifteen 100 mm x 100 mm x 100 mm cubes and four 100mm x 100mm x 500mm prisms.

Before casting, the workability of the mixes was determined using the slump test. Specimens (cubes and prisms) were cast in steel moulds and placed in a mist room at 20^{o}C and 95% RH for 24 hours until demoulding. Thereafter, all cubes and two of the prisms were placed in water at 20^{o}C. The remaining two prisms were left to air cure in a controlled chamber set at 20^{o}C and 55% RH. The prisms were used for the determination of length change whereas the cubes were used to determine the compressive strength. All testing was in accordance with BS1881.

RESULTS AND DISCUSSION

Chloride Penetration. The results plotted in Figure 1 show that the replacement of portland cement by fly ash has significantly increased the susceptibility of concrete to chloride penetration. The larger the replacement, the more vulnerable the concrete became. The presence of silica fume appears to ameliorate the situation but only to a certain extent, namely as long as the fly ash is within 25% of the binder content. On the other hand, GGBFS has consistently resulted in reducing the vulnerability to chloride penetration even at very high replacement level. Silica fume is shown to further improve this performance.

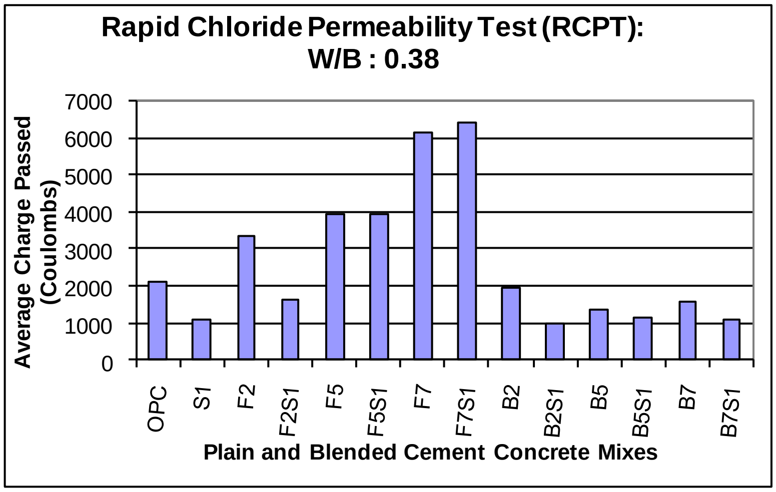

Fig. 1. Effect of Replacing Cement by Pozzolanic Industrial By-product

Although it might be tempting to generalise that one should not increase the fly ash level beyond 25%, the authors believe that this behaviour has been caused by the fact that the mixes have been cured for only 7 days. Indeed, Malhotra has demonstrated the possibility and feasibility of producing high strength high performance concrete using high volume fly ash replacement [Malhotra, 1999]. Thus, it is believed that a responsible attitude is to insist on a different regime of curing when using fly ash in high volume replacement rather than putting a limit on the replacement in order not to change the habitual manufacturing procedure. The special properties of fly ash and the advantages of its inclusion to durability and the environment, should be enough reasons to make sure that this particularity is well accommodated.

Workability. While no problems were encountered in the workability of fresh blended binders in the first series, the metakaolin series showed problems related to workability. The presence of MK reduces the workability as reported elsewhere [Larbi & Bijen, 1992]. Special care was taken to compact the specimens well in their moulds and this is further supported by visual examination. Despite low workability in concrete containing MK, full compaction is achievable if special care is taken [Sabir, Wild & Khatib, 1996].

Compressive Strength. Figure 2 shows the long-term compressive strength as affected progressive fly ash replacement. It is clear that the replacement of OPC by fly ash has significantly reduced the compressive strength. Of course, this is expected in concretes that are cured for only 7 days. In this regard, two important points need to be singled out; (1) when fly ash is replacing OPC, curing must proceed much further than 7 days; and (2) a mix design in which fly ash is considered part of the fines should be adopted. Due to the very fine grading and round shape of fly ash particles, adopting such method in mix design carries advantages including gain in compressive strength and improving impermeability and durability [Ravina, 1998].

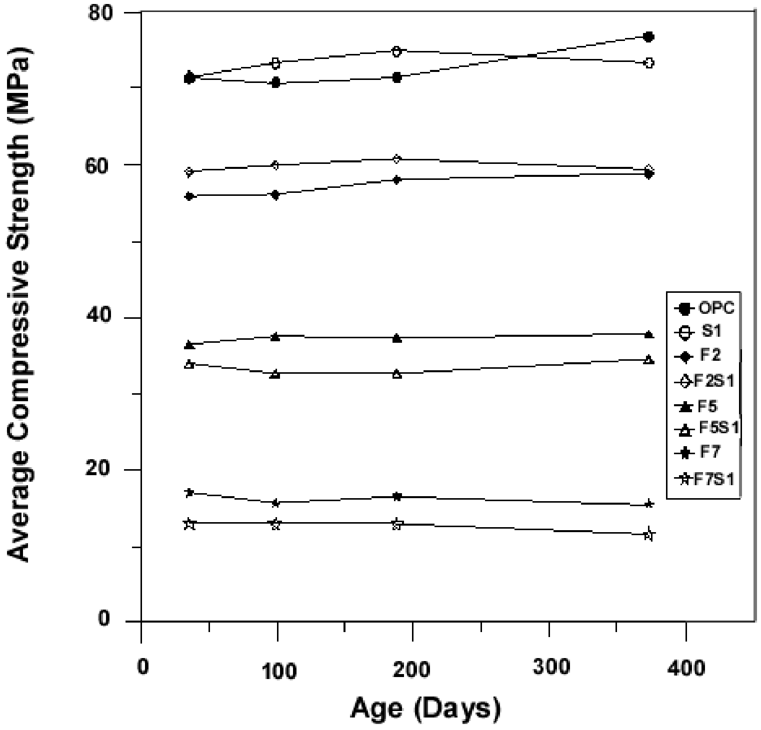

Fig. 2. Long-term Compressive Strength Development in Fly Ash Concretes

Figure 3 shows that compressive strength of blends with GGBFS only suffered a tolerated loss even at 70% replacement. Durability of such concrete has been proven without doubt in the construction of the famous causeway between Saudi Arabia and Bahrain in the aggressive environment of the Gulf [Connell, 1998].

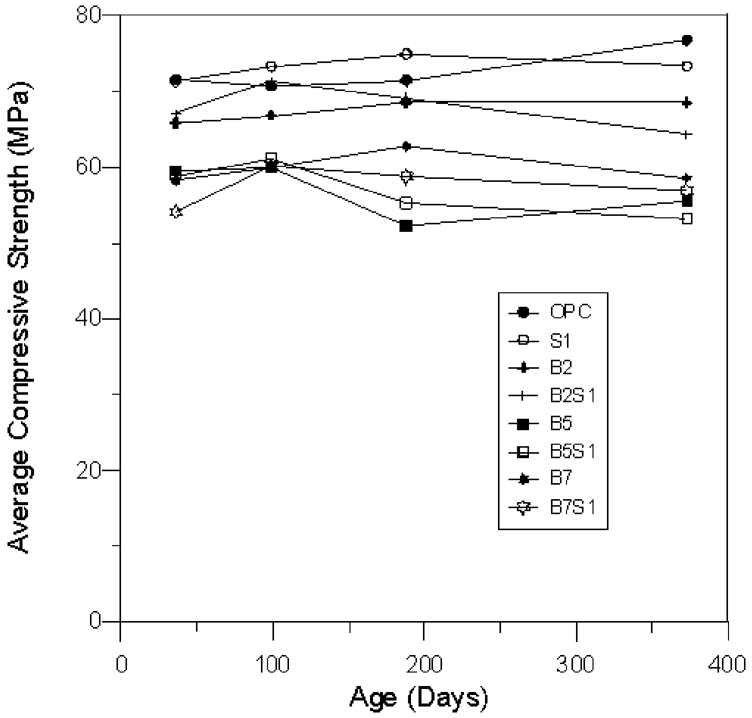

Fig. 3. Long-term Compressive Strength Development in GGBFS Concretes

Figure 4 shows that at 1 day of curing, replacing OPC with MK beyond 5% seems to slightly reduce the compressive strength. However, beyond 1 day of curing, incorporating MK in the mix increases strength and reaches a maximum when 15% of OPC is replaced with MK. Moreover the maximum contribution of MK occurs at 14 days of curing where more than 35% increase in strength is obtained. This effect has been attributed to the exchange in ions between metakaolin and calcium hydroxide that occurs at around 14 days [Larbi & Bijen, 1992]. Thus it may be concluded that the use of metakaolin is evidently significantly beneficial in long-term strength development and is not particularly suitable if early strength is required.

Drying Shrinkage. Another aspect of great significane in metakaolin concrete is its positive effect on drying shrinkage. The length change for air cured specimens at different MK contents is shown in Figure 5. As the MK content increases, the shrinkage decreases. Replacing the PC with 20% MK can reduce the long-term shrinkage by more than 50%. In contrast, the fly ash as well as the GGBFS blends have been reported to produce larger shrinkage values when cured for only 7 days [Ahmed, 2007].

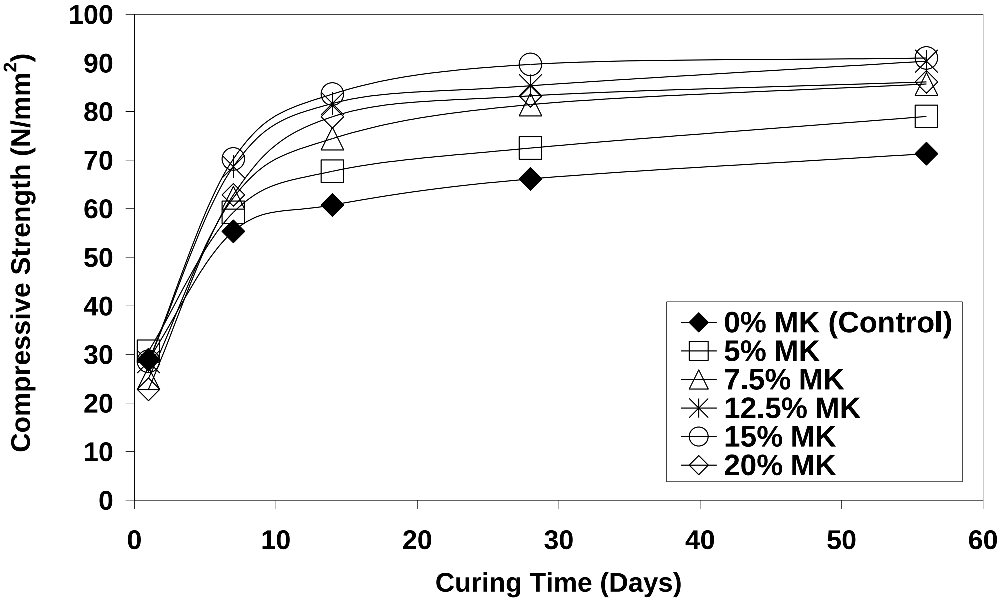

Fig.4. Compressive Strength of Metakaolin Mixes

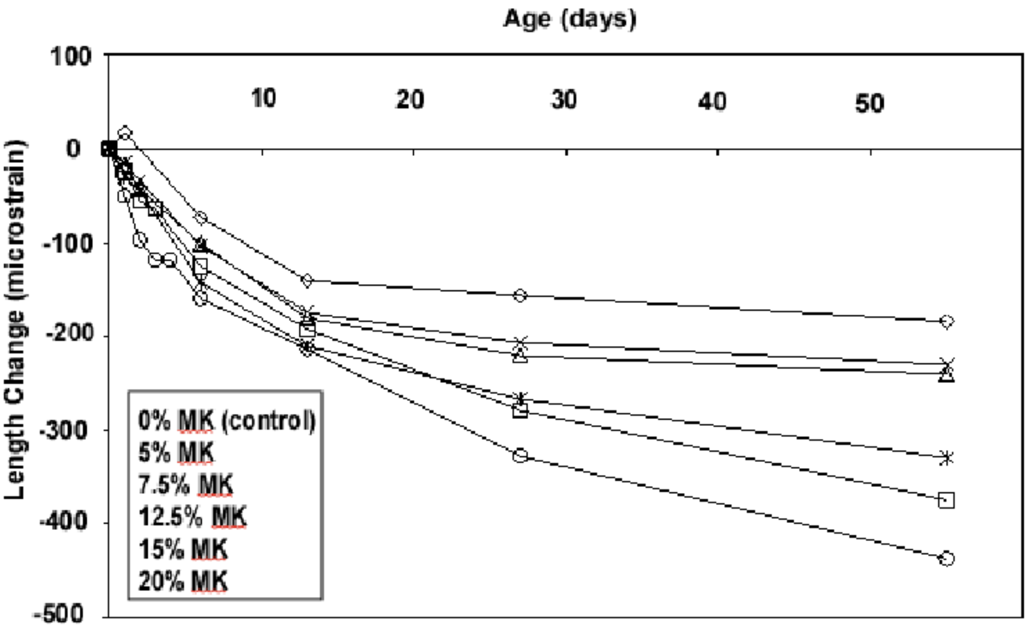

Fig. 5. Length Change for MK Concrete Subjected to Air Curing at 20^{o}C, 55%RH

CONCLUSIONS

The results and the discussion presented in this paper have led to the following conclusions regarding the particularities of certain industrial by-products when used in concrete production.

- Within the usual practice of concrete production that applies curing for only 7 days, progressive replacement of portland cement by fly ash corresponds to a progressive decline in compressive strength as well as a matching decline in resistance to chloride penetration.
- Ground granulated blast furnace slag can substitute cement in large proportions without causing large deterioration to the strength of concrete. There is strong evidence that such concrete is effectively resistant to chloride penetration even when the replacement is as high as 70%.
- The optimum replacement level to give maximum strength enhancement is 15% MK for low water to binder ratio of 0.3. The maximum contribution of MK to strength occurs at 14 days of curing. A systematic increase in MK content of up to at least 20% in concrete leads to a decrease in shrinkage.
- The workability of metakaolin blended cement is reduced as a result of metakaolin replacement. Workability of tertiary blends of portland cement and silica fume together with fly ash or ground granulated blast furnace slag did not significantly differ from the control mix of plain portland cement concrete.
- It may be concluded that the particular characteristics of each of the pozzolanic binder must play important role in the technology that requires producing high performance concrete. Applying the same familiar technology that works for ordinary portland cement will not lead to achieving the desired performance. The task of the designing engineer is to produce suitable mixes that fulfill workability, strength and performance requirements. This task is further entrusted with the necessity of reducing portland cement use and getting rid of industrial waste in a responsible manner. Such task marks a need to engineer the pozzolanic materials such that ultimate environmental and sustainability benefits are achieved.

REFERENCES

AASHTO-T277. (1989). "Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete." (pp. 836-9.). American Association of State Highway and Transportation Officials.

Ahmaruzzaman, M. "A review on the utilization of fly ash." *Progress in Energy and Combustion Science* In Press, Corrected Proof.

Ahmed, M. S. (2007). "Effects of Systematic Increase of Pozzolanic Materials on the Mechanical, Durability, and Microstructural Characteristics of Concrete." *School of Aerospace, Civil and Mechanical engineering* (p. 818). Canberra: University of New South Wales.

Aitcin, P.-C. (2000). "Cements of yesterday and today: Concrete of tomorrow." *Cement and Concrete Research* 30(9), 1349-59.

Connell, M. (1998). "The long term performance of high slag concrete." *Concrete (London)* 32(6), 30-1.

Ganjian, E. & Pouya, H. S. (2009). "The effect of Persian Gulf tidal zone exposure on durability of mixes containing silica fume and blast furnace slag." *Construction and Building Materials* 23(2), 644-52.

Gartner, E. (2004). "Industrially interesting approaches to “low-CO2” cements " *Cement and Concrete Research* 34(9), 1489-98.

Huntzinger, D. N. & Eatmon, T. D. (2009). "A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies." *Journal of Cleaner Production* 17(7), 668-75.

Kayali, O. (2008). "Fly ash lightweight aggregates in high performance concrete." *Construction and Building Materials* 22(12), 2393-9.

Kayali, O. & Zhu, B. (2005). "Chloride induced reinforcement corrosion in lightweight aggregate high-strength fly ash concrete." *Construction and Building Materials* 19(4), 327-36.

Kayyali, O. A. & Haque, M. N. (1988). "Chloride penetration and the ratio of Cl-/OH- in the pores of cement paste." *Cement and Concrete Research* 18(6), 895-900.

Larbi, J. A. & Bijen, J. M. (1992). "Influence of pozzolans on the portland cement paste-aggregate interface in relation to diffusion of ions and water absorption in concrete." *Cem Concr Res, 22 (1992)* 22, 551-62.

Lomborg, B. (2001). *The Skeptical Environmentalist: measuring the real state of the world.* Cambridge University Press.

Malhotra, V. M. (1999). "Role of supplementary cementing materials in reducing greenhouse gas emissions." In Swamy, R.N. (Ed.) *Infrastructure Regeneration and Rehabilitation - Improving the Quality of Life through Better Construction, A Vision for the Next Millenium* (pp. 27-42). Sheffield: Sheffield Academic Press.

Meyer, C. (2009). "The greening of the concrete industry." *Cement and Concrete Composites* 31(8), 601-5.

Mora, E. P. (2007). "Life cycle, sustainability and the transcendent quality of building materials." *Building and Environment* 42(3), 1329-34.

Ravina, D. (1998). "Mechanical properties of structural concrete incorporating a high volume of class F fly ash as partial fine sand replacement." *Materials and Structures* 31(3), 84-90.

Sabir, B. B., Wild, S. & Khatib, J. M. (1996). "On the Workability and Strength Development of Metakaolin Concrete." *Int. Conf. - Concr. in the Service of Mankind: Concr. for Env. Enhancement. Protection* (pp. 651-62). Dundee-Scotland.

Scrivener, K. L. & Kirkpatrick, R. J. (2008). "Innovation in use and research on cementitious material." *Cement and Concrete Research* 38(2), 128-36.

Sukumar, B., Nagamani, K. & Srinivasa Raghavan, R. (2008). "Evaluation of strength at early ages of self-compacting concrete with high volume fly ash." *Construction and Building Materials* 22(7), 1394-401.