Mitigating Climate Change Through the Use of Cement Combinations in Concrete Construction

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Abstract

Supplementary cementitious materials are by-products with lower embodied carbon-dioxide (eCO_2) contents than Portland cement. But while supplementary cementitious materials could be used to mitigate climate change, their intrinsic hydraulicity and delayed hydration reactions could have negative effect on concrete performance and cost. Hence, using 17 binary and ternary cement combinations containing fly ash, silica fume and metakaolin at the water/cement ratios of 0.35, 0.50 and 0.65, this paper investigated the effect of supplementary cementitious materials on the strength development, environmental impact and cost of concrete. The results confirmed that cement combination concretes have lower eCO_2 contents than Portland cement concrete. At equal strengths, binary cement concretes with fly ash up to 55% content and silica fume and metakaolin at not more than 5% contents were cheaper than Portland cement concrete. Also, ternary cement concretes with not more than 5% silica fume or metakaolin content at a total replacement level of not more than 35% were cheaper than Portland cement concrete. At equal strengths of 40, 50 and 60 N/mm^2, results showed that the use of supplementary cementitious materials resulted in a reduction of 5.5-39.0% in eCO_2 content with 50-61.5% of the cement combination concretes being cheaper by 0.1-5.1% than Portland cement concrete. Hence, the use of cement combination in the right proportion would mitigate climate change without having adverse effect on the strength and cost of concrete.

Keywords: blended cement, cement additions, compressive strength, embodied carbon-dioxide, supplementary cements

1. Introduction

Climate change is linked with emissions into the atmosphere and the obvious solution is to reduce carbon footprint (Henson, 2008). The high level of carbon dioxide (CO_2) emissions which stands at about 930kg per tonne of Portland cement produced (The Concrete Industry Sustainable Construction Forum, 2009), has made the construction industry an important sector for emission mitigation strategies. With about 10% of CO_2 emissions being generated by the cement industry (Oxley, 2003), the partial replacement of Portland cement content of concrete by supplementary cementitious materials (SCMs) which are more environmentally compatible due to their low embodied carbon dioxide (eCO_2) content (Table 2), became inevitable in concrete construction. SCMs are by-products of agricultural and industrial wastes and are only used as partial replacements for Portland cement content of concrete due their intrinsic hydraulicity (the need to wait for $Ca(OH)_2$ produced by the hydration reaction of Portland cement) and delayed pozzolanic reaction. Currently, BS EN 197- 1 recognises SCMs like fly ash (FA), silica fume (SF) and metakaolin (MK) among others.

Fly ash is cheap and available (Jones *et al.*, 2006; Antiohos *et al.*, 2007) and due to its spherical shape and low water demand would improve the workability of concrete (Dhir *et al.*, 2002). Also, the use of fly ash is characterized by increased setting times (Langan *et al.*, 2002) and poor performance at early ages (Hassan *et al.*, 2000; McCarthy and Dhir, 2005). However, its improved pozzolanic reactivity with curing age would result in better performance at later ages (Lam *et al.*, 1998). Silica fume and metakaolin are characterized by higher fineness and improved pozzolanic reaction (Mehta and Aitcin, 1990), reduced setting times (Ambroise *et al.*, 1994; Bouzoubaa *et al.*, 2004), enhanced strength (Day, 1992; Uchikawa and Okamura, 1993; Korpa *et al.*, 2008), refined pore structure to increase the permeation resistance of concrete (Bentz *et al.*, 2000; Frias and Cabrera, 2000; Poon *et al.*, 2006; Korpa *et al.*, 2008) and offset the poor performance of fly ash at early ages. However, they are costly and their high water demand would result in workability problems (Bouzoubaa *et al.*, 2004). Hence, for improved performance, ternary combinations of Portland cement, fly ash and silica fume or metakaolin become relevant (Thomas *et al.*, 1999; Khan *et al.*, 2000, Khan and Lynsdale, 2002; Bai *et al.*, 2002). Despite the fact that these supplementary cementitious materials are more environmentally compatible than Portland cement and their use is supported by cement and concrete standards like BS EN 197- 1, BS EN 206- 1 and BS 8500, among others, data from the European Ready Mixed Concrete (ERMCO) confirmed that they are underutilized in construction. This is probably due to the intrinsic hydraulicity and comparatively lower strength of cement combination concrete than Portland cement concrete at equal water/cement ratios.

Concrete is specified, in practice, on the basis of the 28-day compressive strength. But, due to the comparatively lower strength at equal water/cement ratios, equal strength with Portland cement concrete would be achieved by cement combination concretes at lower water/cement ratios necessitating higher cement contents with possible implications on cost and eCO_2 contents. Hence, in order to ascertain that cement combination concrete would mitigate climate change without negative implication on concrete strength and cost, this paper examined the eCO_2 contents and cost implication of binary and ternary cement combination concretes at equal 28-day strengths of 40, 50 and 60 N/mm^2.

2. Experimental Materials and Methods

The cements consisted of ordinary Portland cement (PC, 42.5 type) conforming to BS EN 197- 1, siliceous or Class F fly ash (FA) conforming to BS EN 450, silica fume (SF) in a slurry form (50:50 solid/water ratio by weight) conforming to BS EN 13263- 1 and metakaolin (MK) conforming to BS EN 197- 1. The physical properties of the cements are presented in Table 1.

The aggregates consisted of 0/4mm fine aggregates and uncrushed 4/10 mm and 10/20 mm coarse aggregates of varied shapes. Potable water, conforming to BS EN 1008, was used for mixing and curing the concrete specimens. To achieve good cohesion within a consistence level of S2 defined by a nominal slump of 50-90 mm in BS EN 206- 1, a superplasticiser (a carboxylic ether polymer) conforming to EN 934- 2 was applied to concrete during mixing. Concrete mix designs, at the water/cement ratios of 0.35, 0.50 and 0.65, were based on BRE Design Guide (Teychenne *et al.*, 1997), selected cement combinations (Table 3) and a free water content of 165 kg/m^3 to avoid an excessively sticky mix.

Concrete was prepared to BS EN 12390- 2 and tests were carried out to determine the cube compressive strengths of the specimens. The specimens were cast, cured under a layer of damp hessian covered with polythene for about 24 hours, demoulded and cured in water until the tests' dates. Compressive strengths at 28 days after casting were obtained, in accordance with BS EN 12390- 3, using two replicates of 100 mm concrete cubes. Test specimens were loaded to failure using the Avery Denison crushing machine with a base load of 10kN at a loading rate of 7.0 kN/m^2. Using the mix proportions, the material costs and embodied carbon dioxide (eCO_2) contents of concretes were obtained as the summation of the costs and eCO_2 contents of the constituent materials at the different water/cement ratios using the costs and eCO_2 values presented in Table 2. The costs, eCO_2 contents and strength values were interpolated to obtain their values at equal 28-day strengths of 40, 50 and 60 N/mm^2 (Table 4).

Table 1: Physical properties of cements

Property	Cements			
	PC	FA	MK	SF
Blaine fineness, m^2/kg	395	388	2588	1)
Loss on ignition, % 2)	1.9	6.1 3)	0.9	2.7
Particle density, g/cm^3	3.17	2.26	2.51	2.17
% retained by 45µm sieve 3)	-	11.0	-	-
Particle size distribution, cumulative % passing by mass 4)				
125 µm	100	100	100	100
100 µm	98.2	99.2	100	100
75 µm	93.2	96.5	99.8	100
45 µm	81.8	87.0	99.4	100
25 µm	57.1	66.2	96.0	98.8
10 µm	30.1	40.6	76.2	93.8
5 µm	13.5	24.1	50.7	87.5
2 µm	5.6	10.9	18.2	85.5
1 µm	2.9	4.8	4.7	78.7
0.7 µm	1.3	1.9	1.4	50.7
0.5 µm	0.2	0.3	0.1	10.5

1) Fineness for SF,= 15,000-30,000 m^2/kg (Holland, 2005)
2) In accordance with BS EN 196-2 (except for FA)
3) In accordance with EN 450- 1
4) Obtained with the Laser Particle Sizer

Table 2: Costs and embodied CO_2 contents of concrete constituent materials

Concrete Constituent Material	Cost of Material [1], £/tonne	eCO_2 Content of Material [2], kg/tonne
Portland cement (PC)	60.00	930
Fly ash	20.00	4
Silica fume	140.00	14 [1]
Metakaolin	100.00	300 [1]
0/4 mm aggregates	10.00	4
4/10 mm aggregates	10.00	4
10/20 mm aggregates	10.00	4
Water	10.00	0.3
Admixture (superplasticiser)	1300.00	0.72

Sources: [1] Suppliers

[2] Mineral Products Association (MPA) figures

3. Results and Discussion

3.1 Concrete options at equal water/cement ratios

Table 3 presents the 28-day strengths, costs and eCO_2 contents of concrete options at the water/cement ratios of 0.35, 0.50 and 0.65. The environmental compatibility of concrete was examined with the aid of eCO_2 contents of the concretes. The eCO_2 contents of concretes decreased with increasing water/cement ratio and increasing content of the supplementary cements with FA and SF substantially reducing eCO_2 than MK. The material cost of concrete decreased with increasing water/cement ratio. This is because the quantity of the costliest materials, the cements and superplasticiser, decrease with increasing water/cement ratio. However, while FA reduced cost with increasing content, SF and MK increased cost with increasing content. Also, the costs of the ternary cement concretes (though higher than that of their respective FA binary cement concretes) are lower than that of PC concrete at all the water/cement ratios. Hence, if appropriately proportioned, the use of cement combinations could make concrete more economical.

The cube compressive strengths of concretes at 28 days decreased with increasing water/cement ratio. At equal water/cement ratio, Table 3 shows that the cube compressive strengths of FA binary cement concretes are lower than that of PC concrete and they reduced with increasing content of FA. This is probably due to its poor performance (Hassan *et al.*, 2002; McCarthy and Dhir, 2005) arising from increased setting times (Langan *et al.*, 2002). In line with Day, 1992; Uchikawa and Okamura, 1993 and Korpa *et al.*, 2008, the addition of SF and MK resulted in binary cement concretes with strengths comparable with that of PC concrete. This is probably due to their higher fineness (Table 1) and increased nucleation sites resulting in improved hydration reaction (Mehta and Aitcin, 1990) and reduced setting times (Ambroise *et al.*, 1994; Bouzoubaa *et al.*, 2004). Hence, SF and MK as ternary cement components resulted in ternary cement concretes with better strengths than their corresponding FA binary cement concretes. Table 3 also shows that, at equal water/cement ratios, SF concretes exhibited higher strengths, lower embodied carbon dioxide contents and higher costs than MK concretes at equal replacement levels.

3.2 Concrete options at equal strengths

Concrete is specified in practice on the basis of strength and in order to examine the cost and environmental implications of blended cement on concrete construction, Table 4 presents the costs and eCO_2 contents of concrete options at the 28-day strengths of 40, 50 and 60 N/mm^2. Table 4 shows that equal strength with Portland cement concrete were achieved at lower water/cement ratios (and therefore at higher cement contents) by the blended cement concretes. Hence, equal strengths would be achieved at different material contents, material costs and embodied carbon dioxide contents. At equal 28-day strengths, all the cement combination concretes have lower eCO_2 contents than PC concrete and the reduction in eCO_2 content ranges between 5.5 and 39.0%. Hence, these cement combination concrete options are generally more environmentally compatible than ordinary Portland cement concrete.

Table 3: Compressive strengths, costs and embodied carbon-dioxide contents of concretes at different water/cement ratios

Mix Combination	Compressive strength, costs and embodied carbon-dioxide of concrete at 28 days,								
	Strength, N/mm^2			Cost, $£/m^3$			eCO_2, kg/m^3		
	0.35	0.50	0.65	0.35	0.50	0.65	0.35	0.50	0.65
100% PC	80.0	54.0	38.5	50.48	41.82	37.43	449	315	245
80%PC+20%FA	72.0	46.5	30.0	45.86	38.67	34.90	356	250	194
80%PC+15%FA+5%MK	82.0	53.0	33.0	48.23	40.40	36.36	364	259	199
80%PC+15%FA+5%SF	83.0	55.0	36.0	49.04	40.46	36.85	356	250	194
65%PC+35%FA	60.0	35.0	20.0	42.67	36.39	33.46	291	203	162
65%PC+30%FA+5%MK	64.0	42.0	24.0	45.09	37.93	34.90	299	208	166
65%PC+25%FA+10%MK	68.0	43.0	25.0	46.87	39.70	35.83	305	214	169
65%PC+30%FA+5%SF	65.0	43.0	26.0	45.85	38.28	35.36	287	203	162
65%PC+25%FA+10%SF	77.0	49.5	32.0	48.04	40.93	36.66	287	204	162
45%PC+55%FA	42.0	24.0	12.0	38.10	33.55	30.81	199	143	111
45%PC+45%FA+10%MK	47.0	32.5	18.5	42.45	36.21	33.55	217	152	123
45%PC+40%FA+15%MK	50.0	33.0	20.0	44.63	38.06	34.78	224	158	127
45%PC+45%FA+10%SF	57.0	36.0	22.0	43.58	37.24	33.96	199	143	111
95%PC+5%MK	80.0	56.0	41.0	51.51	42.50	38.01	433	305	236
90%PC+10%MK	78.0	54.5	38.0	52.52	43.47	38.51	416	292	229
85%PC+15%MK	76.0	54.0	37.0	53.42	44.25	39.24	400	283	220
95%PC+5%SF	81.5	56.5	41.0	52.51	43.10	38.61	426	301	231
90%PC+10%SF	82.0	59.0	42.5	53.91	44.83	39.48	403	282	222

Table 4 shows that 50-61.5% of the cement combination concrete options investigated at equal 28-day strengths are cheaper than ordinary Portland cement concrete and the reduction in cost ranges between 0.1 and 5.1%. The cheaper cement combination concretes are fly ash binary cement concretes at replacement levels up to 55%, silica fume and metakaolin binary cement concretes at replacement levels of not more than 5% and ternary cement concretes with not more than 5% silica fume or metakaolin at a total replacement level of not more than 35%. Hence, the use of cement combination concrete would result in cheaper and more environmentally compatible concrete if appropriately proportioned. Despite the low strength of fly ash concrete at equal water/cement ratios, Table 4 shows that fly ash would reduce the cost of concrete at equal strengths. Also, compared with metakaolin, silica fume concretes would require higher water/cement ratios and produce concretes with lower costs and embodied carbon dioxide contents than metakaolin concretes at equal replacement levels.

4. Conclusion

Cement combination concretes have lower eCO_2 contents and are therefore more environmentally compatible than Portland cement concrete. At equal strengths, the reduction in the eCO_2 contents ranges between 5.5 and 39.0%. Hence, the use of cement combination would reduce carbon dioxide emission and mitigate climate change.

Fly ash reduced compressive strength and concrete cost. Silica fume and metakaolin, on the other hand, have comparable strengths with Portland cement concrete but would increase concrete cost. However, the supplementary cements would complement each other to produce ternary cement concretes that are cheaper than Portland cement concrete. At equal strengths, the reduction in cost ranges between 0.1 and 5.1%.

At equal strengths, fly ash binary cement concretes at replacement levels up to 55%, silica fume and metakaolin binary cement concretes at replacement levels of not more than 5% and ternary cement concretes with not more than 5% silica fume or metakaolin at total replacement levels of not more than 35% would produce cheaper and more environmentally compatible cement combination concretes than Portland cement concrete.

At equal water/cement ratio, silica fume concretes exhibited higher strengths, higher costs and lower embodied carbon dioxide contents than metakaolin concretes at equal replacement levels. Also, at equal replacement level, silica fume concretes achieved equal 28-day strengths with metakaolin concretes at lower costs and lower embodied carbon dioxide contents than metakaolin concretes.

Hence, if mixed in the right proportion, the use of cement combination concrete would mitigate climate change without any negative implication on concrete strength and cost.

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Table 4: Concrete Options at the 28-day strengths of 40, 50 and 60 N/mm^2

Mix combination	28-day Compressive strength, N/mm^2														
	f_{cu} = 40 N/mm^2					f_{cu} = 50 N/mm^2					f_{cu} = 60 N/mm^2				
	w/c	Cost[1], £/m^3		eCO$_2$, kg/m^3		w/c	Cost[1], £/m^3		eCO$_2$, kg/m^3		w/c	Cost[1], £/m^3		eCO$_2$, kg/m^3	
		Cost	%Diff	eCO$_2$	%Diff		Cost	%Diff	eCO$_2$	%Diff		Cost	%Diff	eCO$_2$	%Diff
100%PC	0.63	37.77	-	251	-	0.53	41.08	-	296	-	0.46	44.01	-	345	-
80%PC+20%FA	0.55	37.04	-1.9	226	-10.0	0.47	39.84	-3.0	267	-9.8	0.41	42.58	-3.3	308	-10.7
80%PC+15%FA+5%MK	0.59	37.52	-0.7	218	-13.2	0.52	39.64	-3.5	249	-15.9	0.46	42.12	-4.3	283	-18.0
80%PC+15%FA+5%SF	0.61	37.32	-1.2	205	-18.3	0.53	39.34	-4.2	235	-20.6	0.47	41.78	-5.1	268	-22.3
65%PC+35%FA	0.46	37.74	-0.1	223	-11.2	0.40	40.21	-2.1	257	-13.2	0.35	42.67	-3.0	292	-15.4
65%PC+30%FA+5%MK	0.51	37.60	-0.5	204	-18.7	0.44	40.30	-1.9	239	-19.3	0.37	43.90	-0.3	284	-17.7
65%PC+25%FA+10%MK	0.52	38.99	+3.2	205	-18.3	0.45	41.72	+1.6	239	-19.3	0.39	44.64	+1.4	276	-20.0
65%PC+30%FA+5%SF	0.52	37.62	-0.4	196	-21.9	0.45	40.29	-1.9	227	-23.3	0.38	43.96	-0.1	267	-22.6
65%PC+25%FA+10%SF	0.57	38.59	+2.2	179	-28.7	0.5	40.93	-0.4	204	-31.1	0.43	43.90	-0.3	238	-31.0
45%PC+55%FA	0.36	37.74	-0.1	195	-22.3	*	*	*	*	*	*	*	*	*	*
45%PC+45%FA+10%MK	0.42	39.09	+3.5	182	-27.5	*	*	*	*	*	*	*	*	*	*
45%PC+40%FA+15%MK	0.43	40.72	+7.8	185	-26.3	0.35	44.63	+8.6	224	-24.3	*	*	*	*	*
45%PC+45%FA+10%SF	0.47	38.26	+1.3	153	-39.0	0.39	41.59	+1.2	182	-38.5	*	*	*	*	*
95%PC+5%MK	**	**	**	**	**	0.55	40.50	-1.4	276	-6.8	0.47	43.94	-0.2	326	-5.5
90%PC+10%MK	0.63	38.93	+3.1	235	-6.4	0.53	42.15	+4.0	275	-7.1	0.46	45.48	+3.3	320	-7.3
85%PC+15%MK	0.62	39.91	+5.7	229	-8.8	0.53	42.92	+4.5	267	-9.8	0.45	46.84	+6.4	317	-8.1
95%PC+5%SF	**	**	**	**	**	0.55	41.05	-0.1	272	-8.1	0.47	44.59	+1.3	322	-6.7
90%PC+10%SF	**	**	**	**	**	0.57	41.87	+1.9	247	-16.6	0.49	45.32	+3.0	289	-16.2

* Mix combination requires lower water/cement ratio than investigated.

** Mix combination requires higher water/cement ratio than investigated.