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High performance concrete incorporating fly ash, nano-silica (nano-SiO2) and micro-silica (micro-SiO2)

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Abstract: High performance concrete (HPC) exceeds the properties and constructability of normal concrete. Normal and special materials such as fly ash, micro silica and nano silica are used to make these specially designed concretes that must meet a combination of performance requirements. There are many good reasons to view fly ash, micro silica and nano silica as blended materials in concrete. In many cases, concrete made with fly ash, micro silica and nano silica performs better than concrete made without them.

In this paper, an effort was made to evaluate the effect of nano-silica (nano-SiO2), micro-silica (micro-SiO2) and fly ash in improving the properties concrete. Firstly, compressive strength of concrete with different percentage of nano-silica (nano-SiO2), micro-silica (micro-SiO2) and fly ash was studied. Secondly, compressive strength of concrete with Ordinary Portland cement (OPC) and Portland fly ash cement (PPC) was studied. Thirdly, compressive strength of concrete with combination of fly ash and micro silica (micro-SiO2) was studied.

Keywords: fly ash, micro SiO2, nano SiO2, high performance concrete

1. Introduction

Concrete is the second most consumed material after water and it shapes the built environment around the world. According to U. S. geological survey, mineral commodity summaries January 2015, the cement production in the world in 2014 is 4.18 billion metric tons [1]. The concrete production was 25 billion metric tons according to Cement Sustainability Initiative (CSI) report [CSI, 2009] [2]. Fly ash and silica fume can be used as cementious materials to enhance strength and durability properties of concrete [3]. These materials can be added as a last step in cement production or when the concrete is made. In the developed world most cement is made industrially into concrete and sold as ready-mix concrete. On a smaller scale, and more commonly in developing countries, concrete is made in situ on the construction site by individual users. Concrete are defined mainly into different categories; conventional concrete, high-strength/ high-performance concrete and nano-engineered concrete etc.

High-performance concrete (HPC) exceeds the properties and constructability of normal concrete. Supplementary cementitious materials (SCM) such as fly ash and micro silica improve concrete properties mainly in two ways; first it help to generate more Calcium-Silicate-Hydrate (CSH) in the pozzolanic reaction with Ca(OH)2, and second it provide denser concrete due to better particle packing. Finally these concrete would be high strength and durable [4, 5].

American Concrete Institute (ACI) defined high-performance concrete as a concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practice [6]. High performance of concrete is achieved by reducing porosity, in-homogeneity, and micro-cracks in the hydrated cement paste and the transition zone. Consequently, there is a reduction of the thickness of the interfacial transition zone in high-strength concrete. The densification of the interfacial transition zone allows for efficient load transfer between the cement mortar and the coarse aggregate, contributing to the strength of the concrete. For very high-strength concrete where the matrix is extremely dense, a weak aggregate may become the weak link in concrete strength [7, 8]

2. Experimental Program

Chemical compositions of cement and Supplementary Cementing Materials (SCM) were analysed usingX-ray fluorescence (XRF) analyser according to EN 196-2 [11] standard.
Concrete cube specimens of 150mm X 150mm X 150mm were prepared according to BS EN 12390-3standard [12]. These specimens were cast from mix designs as given in tables 1, 2 and 3, Compressive strength of concrete cubes tested at 7 days, 28 days and 60 days for compressive strength. Mix designs of world tallest building (Burj Dubai) [10] was analyzed and four mixes of C80 and C60 were done with local materials and compare performances. Apart from that, high performance concrete C70, C80 and C90 are done with ordinary Portland cement (OPC) and Portland fly ash blended cement (PPC) and compare results.

Table 01: Concrete mixture proportions for compressive strength

Concrete Test	Cement OPC (Kg)	Sand (kg)	Coarse aggregates (kg)	Water (l)	Chemical admixture (ml)*	Fly Ash (Kg)	Micro Silica (Kg)	Nano Silica (Kg)
C1 (OPC)	435.00	774	1026	174	4350			
C2 (OPC+1%mS)	430.65	774	1026	174	4350		4.35	
C3 (OPC+3%mS)	421.95	774	1026	174	4350		13.05	
C4 (OPC+5%mS)	413.25	774	1026	174	4350		21.75	
C5 (OPC+10%mS)	391.50	774	1026	174	4350		43.50	
C6 (OPC+20%mS)	348.00	774	1026	174	4350		87.00	
C7 (OPC+1%nS)	430.65	774	1026	174	4350			4.35
C8 (OPC+3%nS)	421.95	774	1026	174	4350			13.05
C9 (OPC+5%nS)	413.25	774	1026	174	4350			21.75
C10 (OPC+5%FA)	413.25	774	1026	174	4350	21.75		
C11 (OPC+10%FA)	391.50	774	1026	174	4350	43.50		
C12 (OPC+20%FA)	348.00	774	1026	174	4350	87.00		
C13 (OPC+30%FA)	304.50	774	1026	174	4350	130.50		
C14 (OPC+40%FA)	261.00	774	1026	174	4350	174.00		
C15 (OPC+50%FA)	217.50	774	1026	174	4350	217.50		

Table 02: Concrete mixture proportions – G70, G80, G90 concrete with OPC and PCC

Concrete Test	Cement OPC (Kg)	Cement PPC (25%FA) (Kg)	Sand (kg)	Coarse aggregat es (kg)	Water (l)	Chemical admixture (ml)*	Fly Ash (Kg)	Micro Silica (Kg)
G70OPC	400		760	900	170	7000	125	20
G80 OPC	420		740	900	170	7500	145	30
G90 OPC	435		740	900	150	7500	145	40
G70PPC		400	760	900	170	7000	125	20
G80 PPC		420	740	900	170	7500	145	30
G90 PPC		435	740	900	150	7500	145	40

*A high range polycarboxilate type super plasticizer, Brand name: Glenium 233

Table 03: Concrete mixture proportions – trials with concrete mixes used in Burj Dubai tower

Concrete Test	Cement OPC (Kg)	Sand (kg)	Coarse aggregates (kg)	Water (l)	Chemical admixture (ml)*	Fly Ash (Kg)	Micro Silica (Kg)
C80 Burj1	380	908	910	132	4200	60	44
C80 Burj2	384	847	865	155	7500	96	48
C80 Burj3	400	830	847	160	7500	100	50
C60 Burj4	376	888	908	169	3000	82	25

*A high range polycarboxilate type super plasticizer, Brand name: Glenium 233

3. Results and discussions

3.1 Chemical composition

Chemical compositions of cement and Supplementary Cementing Materials (SCM)

Table 04: chemical analysis of materials

Material	SiO2 (%)	Al2O3 (%)	Fe2O3 (%)	CaO (%)
cement	20.38	4.79	3.26	64.40
micro silica	98.93	-	0.31	-
fly ash	52.03	32.31	7.04	5.55
Nano silica	99.59	-	0.33	-

According to chemical analysis, it showed that fly ash taken from Norochcholai power plant, can be categories as class F according to general standards. This fly ash low in lime 5.55% (under 15%), and contain a greater combination of silica, alumina and iron 84.34% (greater than 70 percent). Micro silica bought from local supplier has purity of 98.93%. Nano silica bought from Chinese supplier has purity of 99.59%.

3.2 Strength of Concrete

Strength Performance of concrete with fly ash, micro silica and nano silica are shown below.

Table 05: Compressive strength of concrete at 7 days

7Day Comp. Strength (MPa)	1%	3%	5%	10 %	20 %	30 %	40 %	50 %
Nano silica	45.3	44.6	41.4					
Micro silica	48.7	50.1	48.9	52.6	49.3			
Fly ash			46.9	53.0	46.5	40.9	35.3	32.4
Controlled	46.3	46.3	46.3	46.3	46.3	46.3	46.3	46.3

Table 06: Compressive strength of concrete at 28 days

28Day Comp. Strength (MPa)	1%	3%	5%	10 %	20 %	30 %	40 %	50 %
Nano silica	60.8	57.9	54.6					
Micro silica	57.4	62.2	62.1	57.7	54.0			
Fly ash			58.6	61.4	58.6	51.9	50.3	45.5
Controlled	57.7	57.7	57.7	57.7	57.7	57.7	57.7	57.7

Table 07: Compressive strength of concrete at 60 days

60Day Comp. Strength (MPa)	1%	3%	5%	10 %	20 %	30 %	40 %	50 %
Nano silica	61.7	60.7	59.5					
Micro silica	60.2	63.0	63.2	60.4	55.4			
Fly ash			62.7	64.1	62.4	57.8	56.2	54.0
Controlled	59.3	59.3	59.3	59.3	59.3	59.3	59.3	59.3

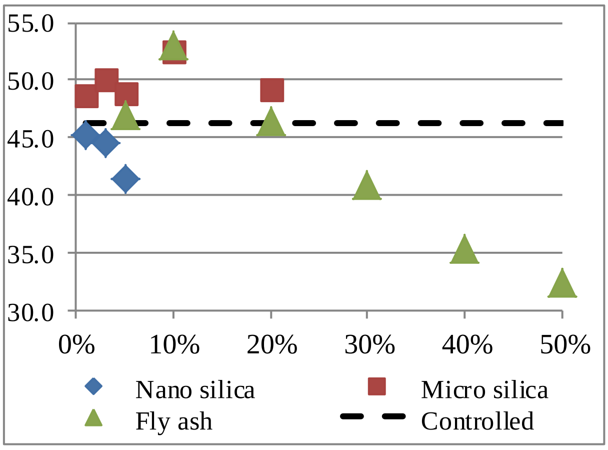

Figure 01: Compressive strength of concrete at 7 days

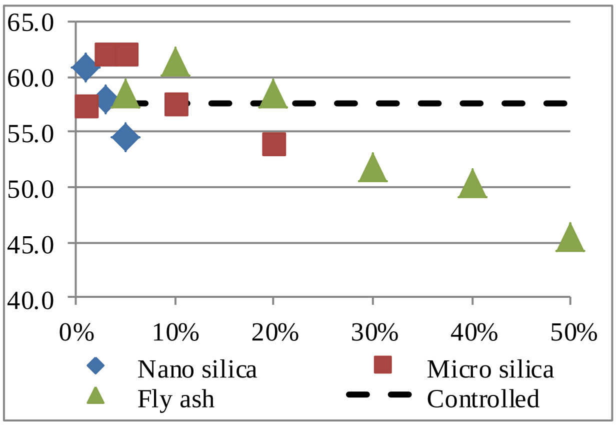

Figure 02: Compressive strength of concrete at 28 days

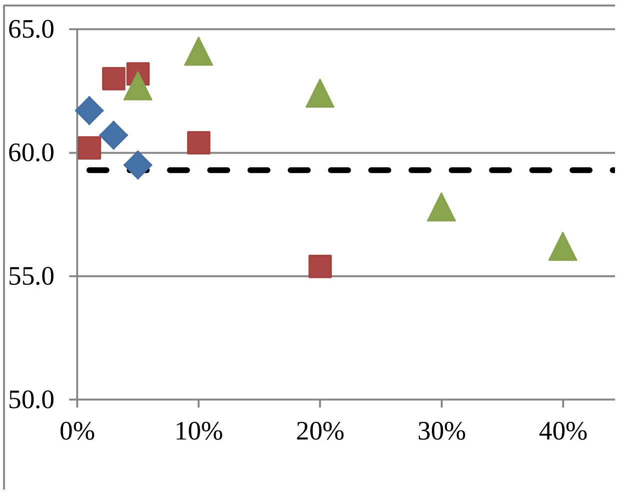

Figure 03: Compressive strength of concrete at 60 days

According to Table 5, 6, 7 and Figure 1, 2, 3, following conclusion can be made; cement can be replaced by fly ash up to 20% - 30% without losing strength of concrete at late ages (60day and 90 days). However, early strength of concrete is affected by fly ash when it uses more than 20%. The best amount of fly ash in concrete would be 10% by considering optimum benefits towards strength. Main benefits of fly ash are workability of concrete mix even at very high percentages. These are really useful for concrete which is to be pumped for longer distances, especially for high rise structures. Main issue with high volume fly ash is to get required strength when increased the amount of fly ash. As the precaution, micro silica is added into system to boost strength with fly ash.

Cement can be easily replaced by micro silica up to 10% without losing strength of concrete at all ages. The best amount of micro silica in concrete would be 3-8%. Main issue when dealing with micro silica is losing workability of concrete mix at higher percentages of micro silica. High range super plasticizers are always recommending using with micro silica.

Cement can be replaced by nano silica up to 5% without losing strength of concrete at late ages (60day and 90 days). However, early strength of concrete is badly affected by nano silica in all cases. The best amount of nano silica in concrete would be 1-3% by considering their cost and optimum benefits. It has been observed by other researchers that the compressive strength of concrete at 7 days and 28 days are maximum with 10% micro silica and 2% nano silica combination and compressive strength of concrete with 2% nano-silica is nearly same as with 5% micro silica

Table 8: Summary of cementitious material used in mix designs of the Burj Dubai Tower

Concrete Grade	Member	Level	Req. flow/ Slump	Req. E-modulus	Cement (Kg)	PFA (Kg)	GGBS (Kg)	Micro Silica (kg)	Total cementitious materials (Kg)
C80	Column & Wall	B2~L40	550±75	43,000 (@90D)	380	60 (12%)		44 (9%)	484
C80	Column & Wall	L41~ L108	600±75	41,000 (@56D)	384	96 (18%)		48 (9%)	528
C80	Column & Wall	L109~L126	650±50	41,000 (@56D)	400	100 (18%)		50 (9%)	550
C60	Column & Wall	L127~L154	650±50	37,600 (@28D)	376	94 (19%)		25 (5%)	495
C50	Beams & Slabs	B2~L108	500±75	-	328	82 (19%)		25 (6%)	435
C50	Beams & Slabs	L109~L154	600±50	-	338	112 (24%)		25 (5%)	475
C35	Blinding	-	125±25	-	300			15 (5%)	315
C50	Internal Column, Wall and Slabs	-	150±25	-	160		240 (57%)	20 (5%)	420
C50	Pile Cap Foundation, Retaining wall, Parking Slab	-	150±25	-	160		240 (57%)	20 (5%)	420
C60	Pile	-	600~750	-	315	105 (23%)		30 (7%)	450

When we analyses mix designs used in world tallest building as shown in Table 8. It can be concluded that optimum amount of cementitous materials are used in all mixes without exceeding the maximum limit defined by most of the standards [9]

This is because concrete mixes having high cement content may give rise to shrinkage, cracking and creep of concrete also increases with the cement paste content. In thick concrete sections restrained against movements, high cement content may give rise to excessive cracking caused by differential thermal stresses due to hydration of cement in young concretes [10, 11]

For high strength concretes, increasing cement content beyond a certain value, of the order of 550 kg/m^3 or so, may not increase the compressive strength.

Always, more than 21% of cement is replaced by other cementitious material (fly ash, GGBS, micro silica). Micro silica is used in all 10 mix designs, 60Kg to 112 Kg (5% to 9%) per cubic meter of concrete. Fly ash is used in 7 mix designs, 15Kg to 50 Kg (12% to 24%) per cubic meter of concrete**.** It is clear that, adding fly ash and micro silica become essential when high strength/ high performance concrete are designed.

Table 9: Results of trail mix (Burj Dubai mix designs with local materials)

Sample Ref.	Compressive Strength (MPa)		
	1D	7D	28D
C80 Burj1	27.7	62.3	81.7
C80 Burj2	39.3	68.4	83.0
C80 Burj3	38.0	72.1	93.0
C60 Burj4	22.6	47.4	62.3

As shown in the Table 9, it can be concluded that it is not difficult to achieve high strength concrete performance with local raw materials to get strength requirements for high rise building in Sri Lanka. Mix designs related to above 4 mixes can be found in Table 2. 28 days of strength of mixes C80 Burj1, 2 and 3 are above grade 80 and full fill requirements. 28 days of strength of mix C80 Burj4 is above grade 60 and full fill requirements.

Table 10 and Figure 4 witnessed that high strength concrete (G70, G80, G90) with OPC and PPC has almost similar strength at 28 days (only 1~3% different. However, early strength of concrete with fly ash blended cement tend to be considerably low as 10~13%. So, structures with early strength is not significant, it is always recommend to go for fly ash blended cement for better performance knowing that other workability and durability benefits given by the fly ash.

Table 10: Results of trail mix with G70, G80, G90 concrete with OPC and PCC

Sample Ref.	Compressive Strength (MPa)		
	1D	7D	28D
G70 (OPC)	41.2	71.2	85.6
G80 (OPC)	43.6	79.5	87.2
G90 (OPC)	46.8	84.8	105.7
G70 PPC (25% FA)	37.2	68.2	83
G80 PPC (25% FA)	38	77.2	86.2
G90 PPC (25% FA)	42.1	82.3	103.4

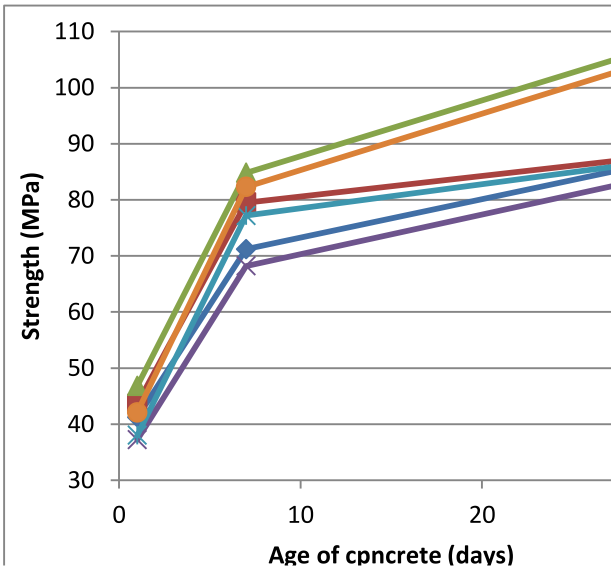

Figure 04: Compressive strength of concrete at 60 days

4. Conclusions

Test results obtained in this study indicate that up to 5% nano silica, 10% of micro silica, 20%-30% fly ash and 5% bottom ash could be advantageously blended with cement without adversely affecting the strength. However, optimum levels of these materials are 1-3% nano silica, 3-8% of micro silica, 10% fly ash and 5% of bottom ash.

Further, a higher amount of fly ash can be used in concrete if a turnery blend like nano silica or micro silica is added into the system. As an example a mix design of world tallest building (Burj Dubai), the fly ash percentage in Grade 80 concrete used for columns and walls level 109~126 were high as 100Kg (18%) with 50 Kg (9%) of micro silica, the usage of cement in this mix design was as low as 400Kg, and other materials sand 830 kg, coarse aggregates (10mm) 847 Kg, admixtures 3% and water: binder ratio was 0.3

In Sri Lanka, in most of the projects fly ash are used in the range of 20-25%. Micro silica with fly ash is used in most of the high rise building projects in the world to get higher strength and extended durability. Micro silica used in all the concrete mix designs of world tallest building, Burj Khalifa in Dubai, it is from 5% to 9% by weight. Fly ash used in all the concrete mix designs of world tallest building, Burj Khalifa in Dubai, it is from 12% to 24% by weight.

It is always recommend optimizing mix designs either with blended cement, cement replacement materials such as fly ash (with or without micro silica) to get highest performance with the concrete. There will always be a better option with blended cement or blended materials with ordinary Portland cement.

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References

[1] S. Jewell, S. Kimball, Mineral commodity summaries 2015, U. S. Department of Interior, U. S. Geological survey

[2] The Cement Sustainability Initiative ACI 2009, World Business Council for Sustainable Development, E-mail: washington@wbcsd.org

[3] Chapter 3; Fly Ash, Slag, Silica Fume, and Natural Pozzolans retrieved from http://www.ce.memphis.edu/1101/notes/concrete/PCA_manual/Chap03.pdf

[4] Michael Thomas, Ph.D., P.Eng., Professor of Civil Engineering, University of New Brunswick, Optimizing the Use of Fly Ash in Concrete, Portland Cement Association (PCA)

[5] ASTM C618 - 12a, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

[6] ACI Committee 232, Use of Fly Ash in Concrete, ACI 232.2R96, American Concrete Institute, Farmington Hills, 1996, PP 1-34.

[7] Portland cement association, Cement and Concrete Basics, Supplementary Cementing Materials, retrieved from http://www.cement.org/basics/concretebasics_supplementary.asp

[8] Mindess, Sidney; Young, J. Francis; Darwin, David., Concrete (2nd edition), 2003.

[9] Summary of concrete mix design for Burj Dubai Tower, retrieved from http://dubai-tower.blogspot.com/2008/08/summary-of-concrete-mix-design-for-burj.htm

[10] EN 196-2 2005, methods of testing Cement – Part 6: Chemical analysis of cement, European Standard, PP 1-24. March 2005.

[11] BS EN 12390-3: 2009, Testing hardened concrete. Compressive strength of test specimens