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Performance of 3rd Generation Locally Available Chemical Admixtures in the Production of SCC

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Abstract

Increasing trend in urbanization and industrialization has necessitated production of high rise buildings with an innovation to make an optimized use of reduced available land in thickly populated areas, which is not possible by standard conventional concrete. Such a different concrete can be created only through different types of admixtures, which when added at various stages of concrete production yield required properties without scarifying the durability and economy of the structure. A proper mix design of self-compacting concrete (SCC) gives improved properties required in fresh state as well as in hardened state thus enhancing the durability of the structure through good bonding between concrete and steel apart from other factors. Present paper gives an outline of the fundamental rheological properties such as flow-ability, passing-ability and stability of self -compacting concrete in fresh state using variety of the locally available chemical admixtures related to 1st, 2nd and 3rdgenerations from various chemicals supplying outlets. ASTM-test methods along with ACI, EFNARC and RILEM specifications and guidelines were followed throughout the experimentation process. It was observed that 3rd generation chemical admixtures gave better performance compared to 1st and 2nd generation admixtures. Flow-ability and passing-ability for the produced concrete were found to be improved by an average of more than 25%. SCC produced was highly stable showing improvement in compressive strength by average of 30%. All this can be attributed to the long chain molecular structure of the Poly-Carboxylate Ether (PCE)in 3rd generation chemical admixtures helping produce highly fluid yet a stable concrete.

Key Words: Self Compacting Concrete (SCC); Mix design; Poly-Carboxylate Ether (PCE); High Range Water Reducer (HRWR); Viscosity Modifying Admixture (VMA); Compressive strength; Normally Vibrated Concrete (NVC); Super-plasticizers (SPs)

1. Introduction

The necessity of the use of a concrete having ability to get compacted without any compactive effort came to board after the durability issues and concerns related to poor compaction of concrete about the various structures in Japan in early 90's. For the creation of a durable structure, adequate compaction is necessary by skilled labor. At that time Japan was also facing severe shortage of skilled labor toget properly compacted concrete for a durable structure. Okamuraand Ozawa [1] proposed the necessity of the use of a new type of concrete that can be compacted in all intricate spaces of the formwork only through gravity as a solution to this problem. Since then number of studies and research efforts have been carried out to improve its various properties and make its production feasible anywhere in the world according to local environment using locally available materials. Self-Compacting Concrete (SCC) is the outcome of the technological advancement in the area of underwater concrete technology where mix is so proportioned that it ensures high fluidity and high resistance to water dilution and segregation [2]. This has got increasingly wide acceptance especially in Japan and generally in other parts of the world for casting congested reinforced concrete structures [3].SCC has effectively been used to accelerate the construction progress without scarifying the mechanical properties of the structure[2, 5].

Properly tailored mix design of SCC helps in maintaining the high workability which is necessary for placement ease ensuring the adequate stability and homogeneous distribution of the engineering properties and durability. As a result SCC exhibit more stability in strength compared to that of normally vibrated concrete (NVC). All this workability and strength/ durability improvements are because of the inclusion of high range water reducers (HRWR) and VMA.Properly proportioned dosages of the materials may yield the resulting concrete having engineering properties even far better beyond our expectations [3, 4].

1.1 HRWRor Super-Plasticizers (SPs); in General

In general, the performance of the innovative types of concretes being used today is mainly due to tailored rheological properties of the mix [2]. If hydration of the cement particles is controlled according to our needs then flow behavior of the cement system during early hours will become better and hardened properties of the concrete will be improved. This is obtained by use of chemical admixtures likeHRWR or Super-Plasticizer (SP) being more effective than the plasticizers [5]. These chemical admixtures improve workability level at same w/c ratio required for specific strength and durability considerations. The improved workability is due to the dispersion of hydrating cement particles [3]. The effects of SPs depend mainly on chemical composition of the cement like alkali, C_3A and the sulfate contents.All types of SPs control the reactivity of C_3A and C_4AF by adsorption in large concentration on their surfaces than on those of C_3S and C_2S. Without super-plasticizer, former compounds have positive zeta potential and later have negative zeta potential and coagulation of cement particles occur due to electrostatic potentials that are opposite to each other. But all component minerals in cement will have negative zeta potential when mixed with any super plasticizer resulting in improved fluidity with lesser water due to electrostatic repulsion[2,4, and 6].

Today, from compositional view point (Figure 1)commercially available chemical admixtures can be classified in to three generations or categories based upon their major ingredients as under [5, 12]:

1. Ligno sulfate based polymers
2. Sulfonated condensates of Malamine and Nephthalene (SMF and SNF) and
3. Polycarboxylate Ether (PCE) polymers

The relevant chemical structures for these are shown in figure 1below.

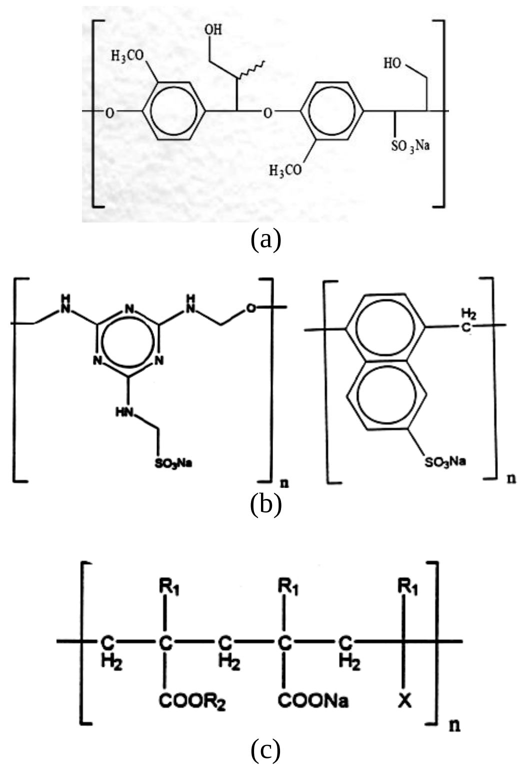

Fig. 1 Molecular structures of (a) Lignosulfates b) SMF and SNF and (c) PCE- where R_1 stands for H or CH_3,R_2 for polyethylene oxide and X is a polar or ionic group [2,17]

1.2 Rheological Properties of 3rd Generation Chemical Admixtures

All HRWRs break down the affinity between cement particles by producing heavy –ive charge density by engulfing them through "surface adsorption" and further reducing re-agglomeration tendency by producing electrostatic forces [10] Amongst the variety of SPs, 3rd generation super-plasticizersi-e PCEs [12] are chemically different and have also been found to be more effective than those related to other two generations. In SMF and SNF, SO^-_3surround the cement particles producing high zeta potential whereas in PCEs, COO^- surrounds them with less electrostatic force.

The molecules of poly-carboxylates, also known to be having "Comb type" structure, consist of an-ionic backbone and non-ionic side chains as shown in figure 2 [11].

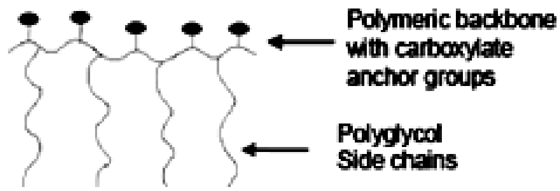

Fig.2 Molecular structure of PCE based polymers [6]

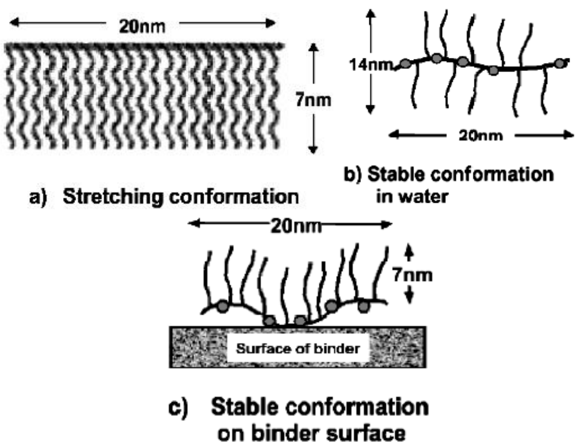

Fig.3 PCEs polymer layer thickness due to surface adsorption [17]

On adsorption of these carboxylate groups on to cement particles, PCEs produce dispersion among cement grains.

According to Dolvo theory[6] forces between super-plasticized cement particles comprise of i) van der waals forces, $F_{vwd,}$ ii) electrostatic repulsive force, F_{el}, and iii) steric repulsive forces, F_{st}: i.e

$$F_{total}= F_{vdw}+F_{el}+F_{st}$$

All these three types of forces exist in 3rd generation admixtures, whereas for 1st and 2nd generations, only first two types of forces are available. Strong steric repulsive force is caused by overlapping of adsorbed polymers. Available literature shows that strong steric repulsion will exist if the distancebetween these adsorbed polymers is smaller than twice the thickness of the super-plasticizers [6].In 3rd generation, the dispersion is mainly due to very strong steric disgust(due to very long chains of ether) whereas the zeta potential is very small i-e electrostatic repulsion is only the half that of value measured for sulfonate and melamine formaldehyde [6, 11, 12].Figure 4 represents the dominating repulsive forces in PCEs polymers.

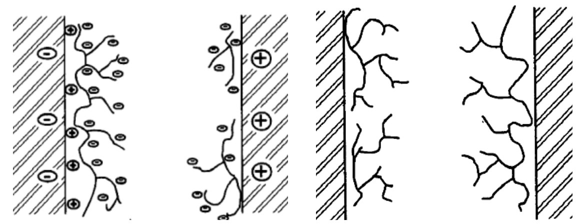

Fig.4 a) Electrostatic repulsion b) Steric repulsion [6]

The shell-type macromolecules obtained through the interaction between the PCE polymers opens progressively showing “slow release mechanism” (Figure 5). These result in improved dispersion and stability of cement particles inhibiting their flocculation even during the cement hydration.

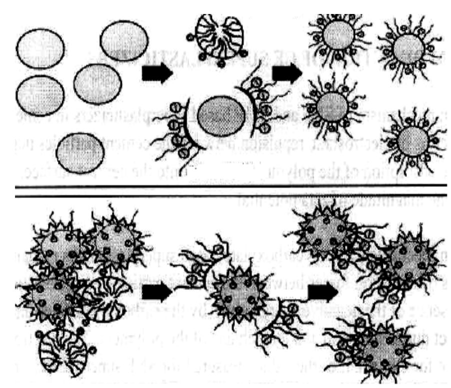

Fig.5 Progressive action mechanism of PCE-molecules engulfing the cement particles [6]

Due to improved efficiency of the concrete mix, the acceptance of PCE for producing a tailored concrete,especially SCC i-e a high performance concrete requiring minimal or no vibration, has dramatically increased during the current decade. [11-13].

1.3 VMA Role in SCCproduction

One dominant property of self- compacting concrete is that it is free from any segregation,contrary to high slump or flowing concrete, which can be had by using Viscosity Modifying Admixtures (VMA) also known as Anti-Washout Admixtures. VMAs were used in mid 70s in Germany and then in Japan in early 80s. After that Europe adopted its wide-spread use in various structures [2]. The most common type used of VMAs is water soluble polysaccharides, like cellulose ether derivatives that bind some of the mixed water, enhancing the viscosity.

1.4 Mechanism of action

Firstly long chained VMA is adsorbed at the surface of the water molecules;it expands and thus increases the mix water viscosity. Then there will be attraction developed between the molecules in adjacent polymer chains causing a gel and increasing further the viscosity. After that polymer chains intervene at higher concentrations showing increased apparent viscosity that results in shear thinning at increasing shear ratemaking the flow easy as shown in figure 6.

Kamal Khayat and Chengwenmiao [2, 18] describe the action of VMA in cement based materials as three fold namely, Adsorption, Association & Intervening.

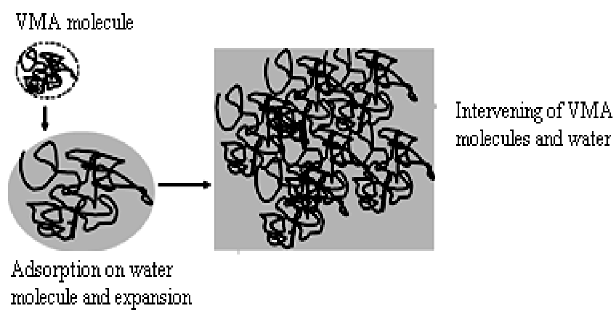

Fig.6 Mechanism of action of VMA, [2, 15-17]

According to ACI –E4-03 &EN 934-2, concrete admixtures to be added in concrete mix should remain well below 5% to alter its properties in fresh and hardened state [2, 15].

The composite action of the HRWR and VMA has been found to be supporting the ease in flow by reducing the yield tress of the concrete mix and reducing the plastic viscosity at increasing shear rate. But all this depends upon the proper and optimized dosage of both these admixtures. No unique mix design is so far available that can be used to get self-compacting concrete giving target values because of the number of variableconstituents involved in the concrete mixhaving different properties in various parts of the world. So, number of trials is required in the laboratory under controlled conditions with some allowance for site condition.

Very little work has been done, so far, to explore the effects of PCEs based 3rd generation chemical admixtures in the production of self-compacting concrete. Most work is related to the use of Secondary Replacement Materials (SRM) like rice husk ash to get SCC and High Performance Concretes (HPCs) in various institutions of the country [19-21]. While in the following experimentation, a comparative work between 2nd and 3rd generation chemical admixtures has been carried out to finalize the mix design, in which the 3rd generation admixtures were found to be more effective as compared to those of 2nd generations.

2. Experimentation

Total of about 35 laboratory trials producing 150 samples were produced under controlled conditions. The guidelines of EFNARC-05 [14] and ACI-237-07 committee report [13] were followed during the trials. The results of mixes in which PCEs admixtures were used showed better performance as regards to basic properties defining SCC due to improved rheological behavior as compared to other two types of admixtures.

2.1 Material used:

Various commercially available admixtures available in the local market from five various outlets were used. These admixtures were related to SMF, SNF and PCEs families.

OPC confirming to EN-197, silica fume having particle size varying between 0.1 to one micron, Lawrence-Pur sand having maximum size of 4mm and Chenab sand, which is finer than that of Lawrence Pur sand, were used as fine aggregates. Margla crush with two fractions of 12mm to 8mm and 8mm down was used.

To control the concrete temperature, chilled water was used along with ice cooled aggregates in saturated surface dry condition (SSD). Similar laboratory conditions were maintained throughout the experimentation process to avoid any conflicting results. The average laboratory temperature was 30^{0}Cwith relative humidity at 75%.

The chemical admixtures from five outlets available in the local market were collected and used for experimentation as shown in table 1 and figure 7 and 8.

Table 1 Admixture sources with chemical families and number of trials

Source	Admixture type	No. of trials
A	SMF,SNF & PCEs	09
B	SMF,SNF & PCEs	13
C	SMF,SNF & PCEs	05
D	SMF,SNF & PCEs	05
E	SMF,SNF & PCEs	03

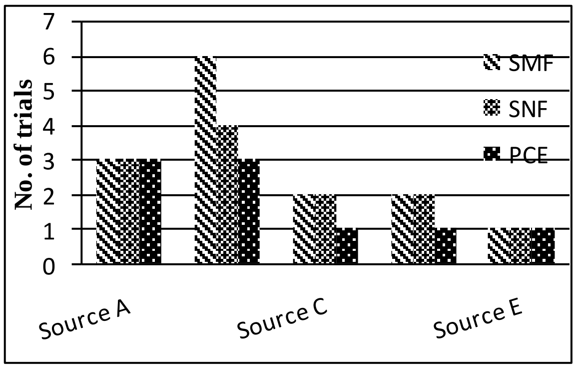

Fig.7 Contribution of various admixture families from different sources.

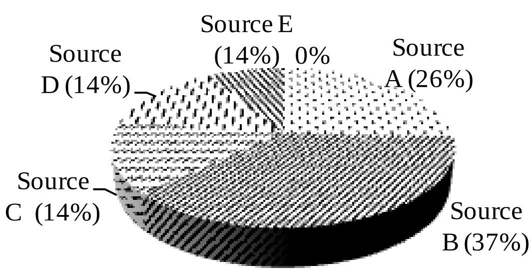

Fig.8 % contribution of various sources in total of trials

Various properties of the materials used in the trials are given in tables 2 - 5.

Table 2: Specific gravity and bulk density of fine aggregates

Sr .#	Sieve Size	Wight retained (g)	%age weight retained	Cumulative % retained	% weight passing
1	4.75 mm	005	00.5	000.5	99.5
2	2.36 mm	004	00.4	000.9	99.1
3	1.18 mm	002	00.2	001.1	98.9
4	0.60 mm	015	01.5	002.6	97.4
5	0.30 mm	925	92.5	095.1	04.9
6	0.15 mm	047	04.7	099.8	00.2
	Σ	998	99.8	199.6	
			Fineness Modulus		1.996

Table 3: Fineness modulus of Lawrence-pur sand (Sample Weight 1000gm)

Sr. No.	Type of Fine Aggregate	Specific Gravity (Relative Density)		Bulk Density (Kg/m^3)	
		By Water displacement	By conical Flask	Loose State	Rodded State
1	Lawrance Pur Sand	2.61	2.75	1629	1837
2	Chenab Sand	2.36	3.4	1834	1907

Table 4: Fineness modulus of Chenab sand (Sample weight 1000gm)

Sr. No	Sieve Size	Wight retained (g)	%age weight retained	Cumulative % retained	% weight passing
1	4.75mm	009	00.9	000.9	99.1
2	2.36mm	026	02.6	003.5	96.5
3	1.18mm	097	09.7	013.2	86.8
4	0.60mm	212	21.2	033.4	66.6
5	0.30mm	598	59.8	093.2	06.8
6	0.15mm	054	05.4	098.6	01.4
	Σ	996	99.6	242.8	
	Fineness Modulus			2.428	

Table 5: Fineness modulus of Margla crush

Sr. No.	Sieve Size	Wight retained (g)	%age weight retained	Cumulative % retained	% weight passing
1	37.50mm	000	000.0	000.0	100.0
2	19.00mm	009	000.9	000.9	099.1
3	09.50mm	571	057.1	058.0	042.0
4	04.75mm	407	040.7	098.7	001.3
5	02.36mm	012	001.2	099.9	000.1
6	01.18mm	000	000.0	099.9	000.1
7	0.600mm	000	000.0	099.0	000.1
8	0.300mm	000	000.0	099.9	000.1
9	0.150 mm	000	000.0	099.9	000.1
	Σ	999	999	653.5	
	Fineness Modulus			6.53	

2.2 Binder Characteristics

OPC confirming to EN197-1 and ASTM C 150 was used along with silica fume having the properties summarized in tables 6 and 7.

Table 6: Properties of Silica fumes

Sr. No.	Property	Value
1.	Particle size	0.1to1µm
2.	Surface Area	20,000m^3/kg
3.	Colour	Grey
4.	Bulk Density	550-700kg/m^3
5.	Chloride content	< 0.1%

Table 7: Water demand and setting time of the binder system

Sr. No	Type of material	W.D	IST	FST	Paste temp	Lab tem
		%	Min	Min	◦C	◦C
1	OPC	28	140	196	24	23
2	Cement+10%Micro silica	41	141	205	24	24
3	Cement+10%Micro silica+2%SP	20	160	207	23	24
4	Cement+20%Micro silica+4%SP	20	171	212	22	25
5	Cement+30%Micro silica+4%SP	25	175	220	23	24
IST=Initial setting time, FST=Final setting time						

Table 8: Typical concrete mix design used for trials

Material Quantities used for Mix Design	Item description		Quantity
	OPC		13.10 Kg
	Silica Fume		1.30 Kg
	Lawrenecpur Sand		19.75 Kg
	Chenab Sand		03.50 Kg
	Margala Crush(SSD Condition)	12mm-8mm size	14.50 Kg
		< 8mm size	21.84 Kg
	HRWR (SMF, SNF & PCE)		1.25L /100Kg
	VMA (used only for concrete mix having PCE admixture)		0.85L /100Kg

Table 9: Applicable ASTM / EN standards [9, 12-14]

SCC Property	Test Methods	Applicable ASTM & EN Standards
Flow Ability	Slump Flow Test	ASTM- C1611/ C1611M-05 & EN-12350-2/I
Passing Ability	J-Ring / Blocking ring Test	ASTM C I621/ C1621M-06
Static Stability	Static segregation Test (Column type)	ASTM C-1610/ C1610M-06a

3. Mixing of concrete

Concrete mixer was rotated at constant maximum speed of about 550rpm for all the trials with same sequence of mixing ofingredients. Firstly, dry mixing of the binder system was done for a period of about 3minutes. Then wet mixing with water was done for 5minutes. HRWR was added to the wet binder mix system, then fine aggregates and then coarse aggregates were introduced in the mixer and mixing was done for three and five minutes, respectively. Then VMA dose was put in rotating mixer. The mixture was assessed visually to check the physical condition of the resulting mix.

4. Testing and Casting of the concrete Mix

After mixing the concrete, the basic properties of the concrete namely "flow-ability, passing-ability and segregation resistance" were assessed (Figures 9 to 13) following standard ASTM test methods and the ranges given in ACI 237-07 and EFNARC-05 [9, 12-14]for each trial (Table 10).Before performing any next test, the mix was re-agitated for one minute and test performed. After performing all three tests for each trial, the concrete was put in the cylinders for testing the compressive strengths at the age of 28 days.

Table 10: Ranges/Target values established for the trials [13-14]

Sr. No.	Property	Ranges/ Target Values
1	Avg. f_c'	6000 psi (41MPa)
2	Slump flow	550-650 mm
3	VSI	0= Highly stable 1=Stable, 2= Unstable 3= Highly unstable
4	Passing Ability	0-25mm = Good 25-50mm=Medium >50mm =Poor
5	% Segregation	< 10% by ACI237-07 < 15% by EFNARC-05

Fig.9 Concrete mixing in progress

Fig.10 Slump flow test (ASTM-C1611/C1611M)

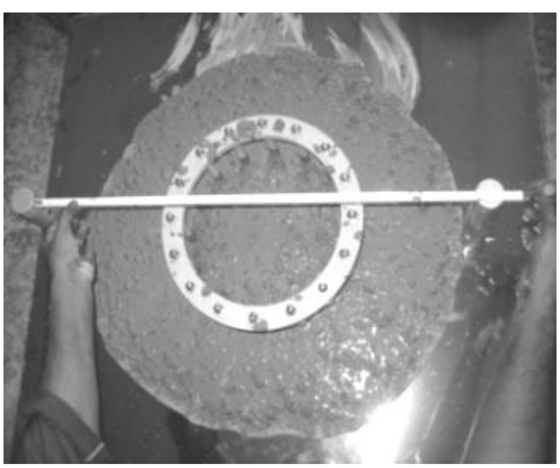

Fig.11 J-Ring test (ASTM C1621/C1621M)

Fig.12 Static stability test (ASTM C1610 /C1610M)

Fig.13 Capped Concrete filled cylinders for compressive strength tests

5. Test Results

Figure 14 displays graphically the percentage of the trials confirming to the target values established for the trials which was found to be 20%n

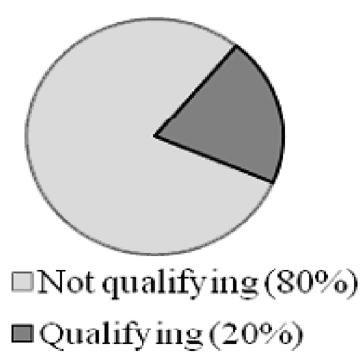

Fig.14 Percentage of trials qualifying the target values

Following table gives the detail of the properties of the trials conducted in the laboratory.

Table 11 Resulting properties of the trials (*Material accumulated in the Centre of flow)

Source & dmixture ype		S. No	Average f'c		Slump Flow Test (ASTM-C1611)		-Ring Test (ASTM-C1621)	olumn egregation Test (ASTM-C1610)
					Slump Flow value	VSI=Visual stability Index	.A= S.F- J.ring flow)	
			MPa	PSi	(mm)		mm	% Segregation
Source A	SMF	1	27.83	4036	475	3	35	33
		2	31.50	4567	530	2	40	23
		3	26.83	3890	500	3	35	28
	SNF	4	36.61	5308	545	3	55	30
		5	40.00	5800	505	2	105	35
		6	39.86	5780	450	2	38	28
	PCE	**7**	**48.34**	**7010**	**655**	**1**	**18**	**09**
		8	**47.13**	**6834**	**645**	**1**	**15**	**07**
		9	**48.01**	**6961**	**640**	**0**	**20**	**10**
Source B	SMF	10	36.90	5350	540	2	60	25
		11	35.95	5213	525	>3	55	30
		12	26.52	3845	475	3	75	32
		13	29.21	4235	530	2	100*	40
		14	33.00	4785	410	3	60	27
		15	31.40	4560	535	2	55	20
	PCE	**16**	**46.16**	**6693**	**660**	**1**	**25**	**08**
		17	**48.25**	**6996**	**680**	**0**	**20**	**10**
		18	**48.00**	**6960**	**655**	**1**	**19**	**10**
	SNF	19	26.97	3910	534	3	70	45
		20	25.00	3625	425	2	85	55
		21	27.78	4028	545	3	45	24
		22	25.81	3742	455	2	38	27
Source C	SMF	23	32.10	4600	550	3	40	30
		24	35.93	5210	477.5	3	45	19
	SNF	25	36.69	5320	567	2	55	22
		26	38.00	5510	555	2	58	20
	PCE	**27**	**47.57**	**6897**	**674**	**0**	**19**	**10**
Source D	SMF	28	30.75	4459	535	3	68	23
		29	30.50	4422	510	2`	125*	35
	SNF	30	29.00	4205	430	2	87	27
		31	31.00	4495	456	2	55	40
	PCE	**32**	**41.45**	**6010**	**670**	**0**	**25**	**11**
Source E	SMF	33	34.34	4980	430	3	55	21
	SN F	34	34.50	5002	510	3	35	15
	PC E	**35**	**43.10**	**6248**	**640**	**0**	**12**	**08**

Tables 12-16 give information quantitatively about various properties of SCC made from different admixtures from five outlets. (For target values refer to Table 10). In all the cases PCE based admixtures are imparting improved properties to concrete in fresh and hardened states compared to other two types of admixtures.

Table 12: Average f'_c (MPa)

Admixture type	Source				
	A	**B**	**C**	**D**	**E**
SMF	28.72	32.16	34.02	30.63	34.34
SNF	38.82	26.39	37.35	30.00	34.50
PCE(HRWR and VMA)	47.83	47.47	47.57	41.45	43.10

Table 13: Average Slump flow (mm)

Admixture type	Source				
	A	**B**	**C**	**D**	**E**
SMF	501.67	502	513.75	522.5	430
SNF	500.0	501.33	561	443.0	510
PCE(HRWR and VMA)	646.7	665	674	670	640

Table 14: Average V.S.I values

Admixture type	Source				
	A	**B**	**C**	**D**	**E**
SMF	2.67	2.50	3	2.5	3
SNF	2.33	2.50	2	2	3
PCE (HRWR and VMA)	0.67	0.67	0	0	0

Table 15: Average P.A (mm)

Admixture type	Source				
	A	**B**	**C**	**D**	**E**
SMF	36.67	67.50	42.50	96.5	55
SNF	66.00	59.50	56.50	71	35
PCE (HRWR and VMA)	17.67	21.33	19	25	12

Table 16: Average percentage (%) segregation resistance value

Admixture type	Source				
	A	**B**	**C**	**D**	**E**
SMF	28	29	24.50	29	21
SNF	31	37.75	21	33.50	15
PCE (HRWR and VMA)	8.67	9.33	10	11	8

Figures 15-19 display graphically the improved trend in all of the properties of the PCEs based concrete mixes compared to those prepared from SMF and SNF type admixtures.

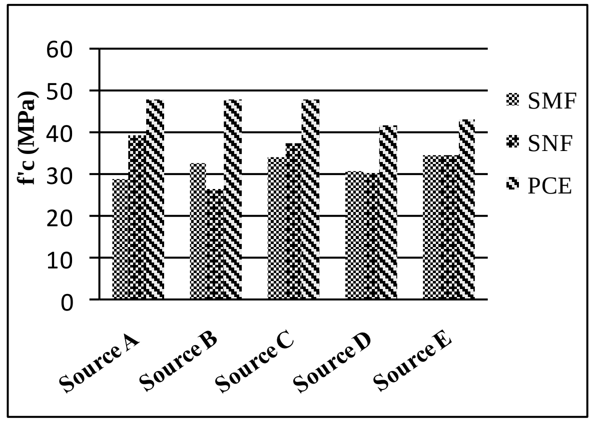

Fig.15 Average f'c(MPa) obtained usingdifferent chemical admixtures

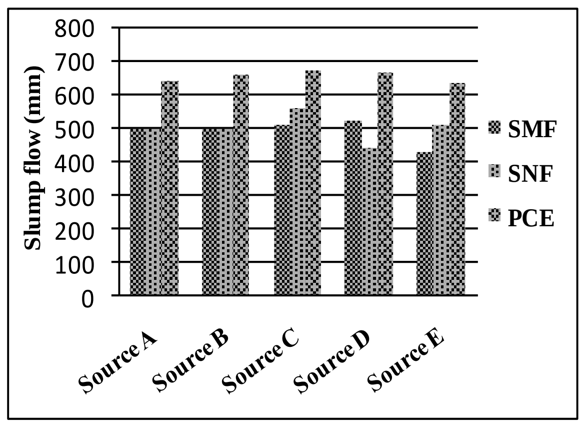

Fig.16 Average slump flow values (mm)

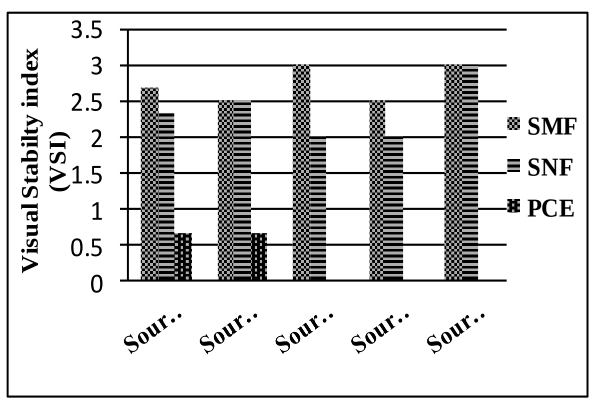

Fig.17 Average V.S.I (Lesser is the value, more stable is the mix, Zero value means highly stable concrete)

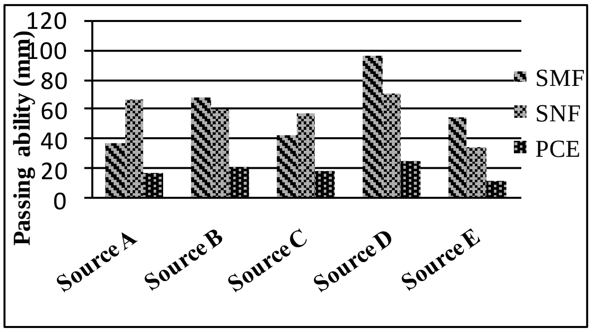

Fig.18 Average P.A (Lesser is the P.A value, concrete is better to pass through dense reinforcement)

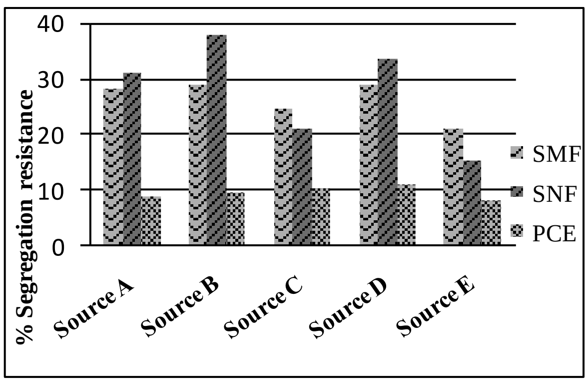

Fig.19 Average percentage segregation resistance. (Lesser value means less segregated concrete)

6. Discussion of the Test Results

i) Fluidity of the concrete Mix

The spread values obtained from the use of SMF and SNF type super-plasticizers were found to show a lesser value as compared to those by PCEs type SP. This is true for SPs from all five outlets. Increase in spread values observed was about 19.95% to 32.25%.

This may be attributed to PCEs having the comb type molecular structure with dominating strong steric repulsive forces reducing the tendency of mix agglomeration. This results in lowest possible yield valuei-e the force required to make the concrete flow. This low yield value is necessary for increased spread of the concrete, a basic property for SCC.

ii) Improved Passing-ability of the Mix

Incorporation of the 3rd generation admixtures gave good passing ability characteristic. All values were falling in "good passing ability" range. Passing ability was improved by about 51.80%. This property makes SCC most suitable for innovative structures having dense reinforcement, especially high rise buildings and buildings in areas prone to earthquake.

iii) Stability and Uniformity of SCC

Homogeneity of the concrete mix was found well in case of PCEs based HRWR used along with VMA. Stability of the mix was observed by Visual Stability Index (VSI) of the concrete spread and also through segregation resistance test which gave results falling in the range of a stable concrete mix. VSI for PCEs admixtures along with use of VMA remained almost "0 or 1" while for other types of HRWRs without VMA were having values mostly of 2 or 3. Also, the segregation resistance of the mix was improved for the mixes with VMA by a minimum value of 46.67%, which is a reasonable value.

iv) Improved Compressive Strength

Use of PCEs type HRWR in combination with VMA has shown a positive impact on the strength of the concrete mix because of the improved homogeneity and density. An increase in compressive strength of about 19.95 % to32.25 % was observed compared to those from other admixtures without VMA. This may have happenedusing VMA producing concretewith proper and equal distribution of the cement content in the mix making stronger CSH gel and resulting in improved strength.

7. Conclusions

The results obtained from the trials have clearly revealed that the present day 3rd generation PCE based admixtures perform much better than those related to first and second generation admixtures.The fundamental rheological properties of the self-compacting concrete i-e fluidity, passing-ability and stability are improved effectively along with the improved compressive strength with an average range of more than 25%. This is only because of its longer molecular chain structure having electrostatic and steric forces helpingconcrete to performbetter.All this shows its suitability for the use in modern self-compacting concrete to get more fluid yet a stable concrete that can encapsulate all the intricate spaces of the formwork.

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