Performance of High Strength Concrete

Dr. R.V. Ranganath, Professor,

Dept. of Civil Engineering,

BMS College of Engineering,

Bengaluru-19.

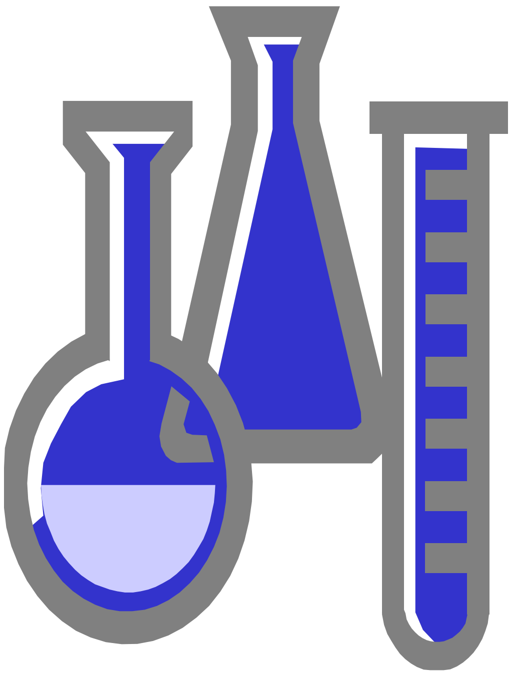
Evolution in Concrete Technology

Main Evolution	Other Phases
Normal-Strength Concrete (Usual/Standard Concrete)	High Density Concrete
↓	Low Density Concrete
High-Strength Concrete	High-early Strength Concrete
↓	
High-Performance Concrete	High Volume Fly Ash Concrete
↓	
Ultra High Performance Concrete	Self Compacting Concrete
	Ductal Concrete
Geo Polymer Concrete	

Hydration chemistry

- Cement chemistry notation

  C=CaO, S=SiO_2, H=H_2O
- Approximately
- $2C_3S+6H$ = $\mathbf{C_3S_2H_3}$+3CH
- $2C_2S+4H$ = $\mathbf{C_3S_2H_3}$+CH
- **C-S-H gel**
  - **Strength bearing phase**

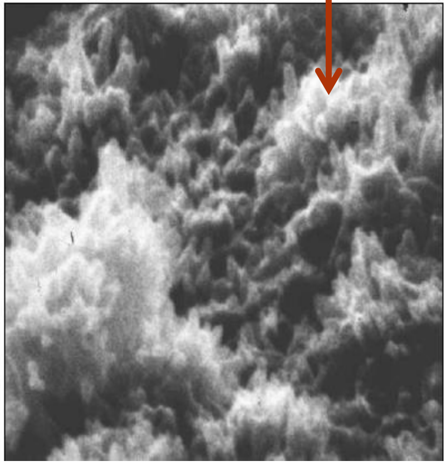


C-S-H gel

- Non-crystalline, insoluble hydrate
  - variable composition
  - complex structure: fibril to ‘crumpled foil’, a few molecules thick
  - huge surface area 100-700 m^2/g: van der Waals bonding gives strength
- Porosity controls properties
  - **10-1000 nm: capillary pores**
  - **1-10 nm: gel pores**

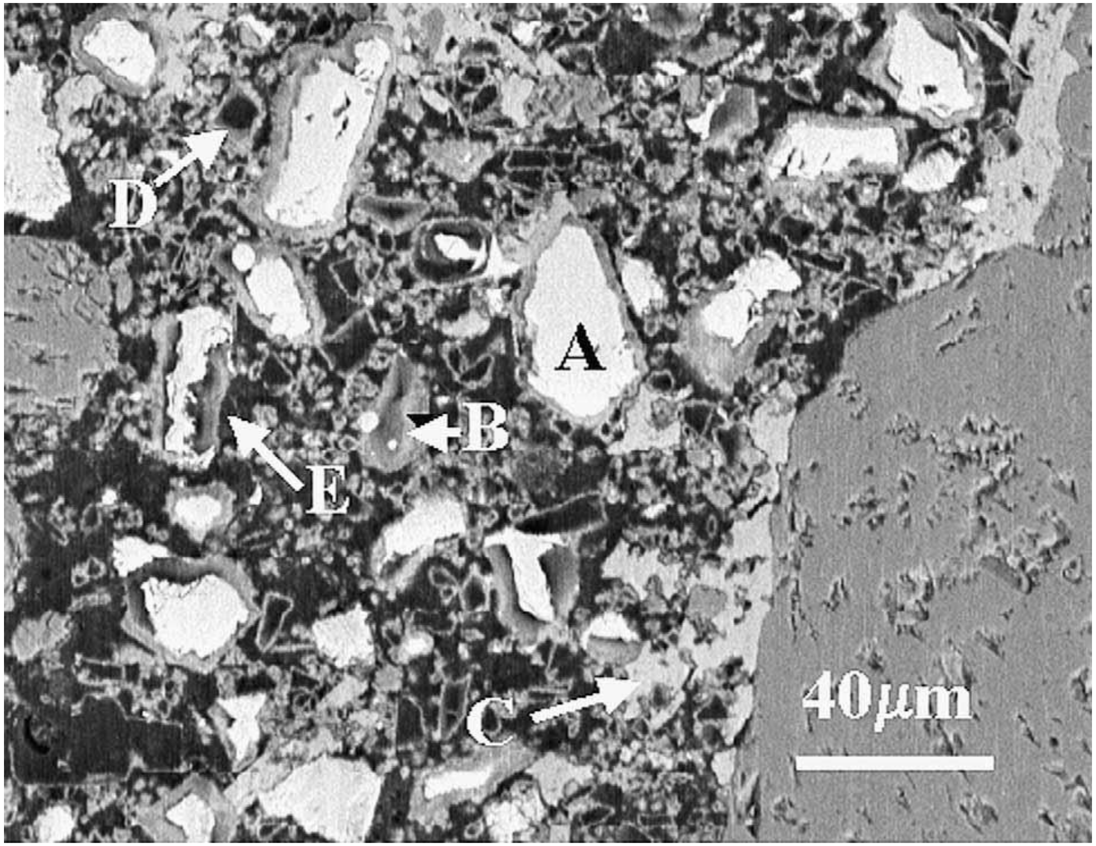
Needle like structures / ettringite..

C-S-H



R.V.Ranganath, BMSCE.

Microstructure

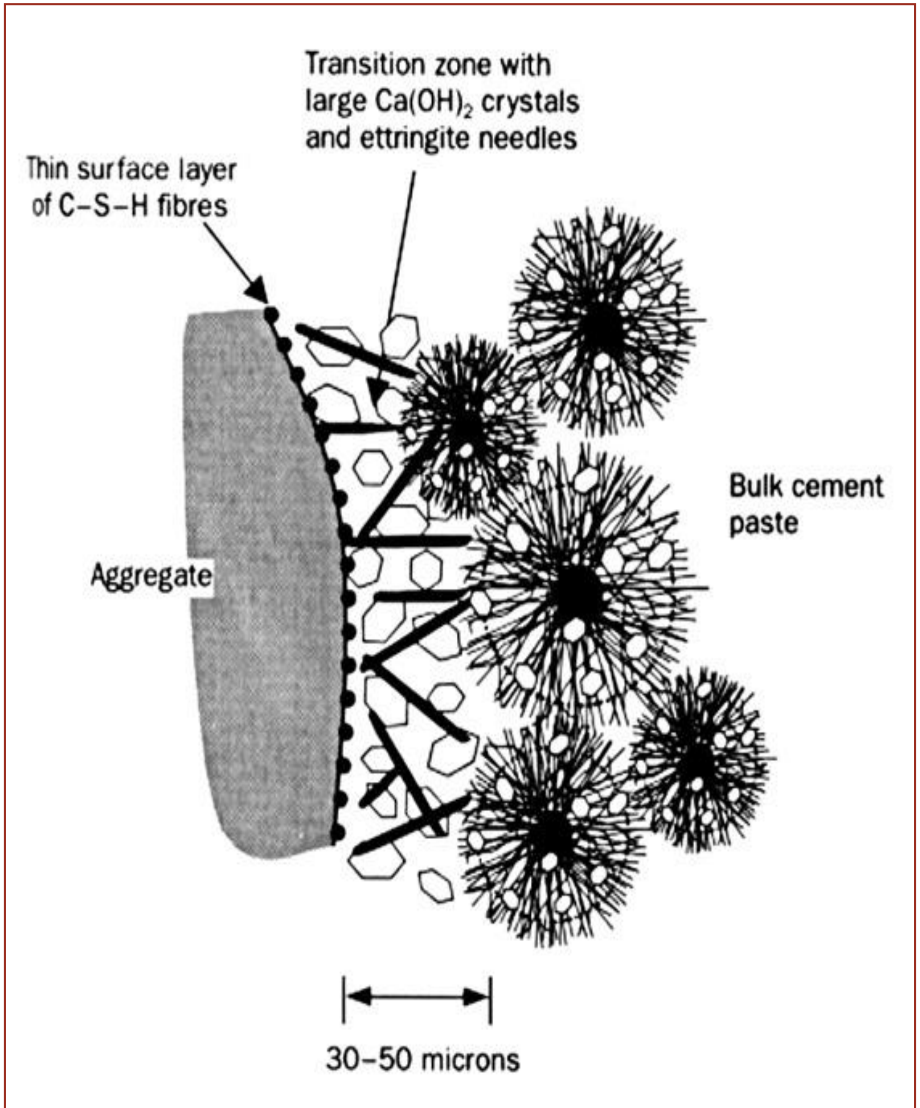


* Sidney Diamond, Purdue U., USA, 2004

- A: Un hydrated cement
- B: Inner CSH
- C: CH
- D,E: Groundmass

CSH too fine to see...

Phases in Microstructure



Failure planes..

HSC/HPC

What is it..?

- High strength/performance concrete (HSC/HPC) with compressive strength in range of 65-100MPa (IS-10262-19, ACI committee, Singapore guidelines, Japan society of Civil Engineers)
- Strength is predominantly decided by the Compressive strength at 28days.
- Performance is governed by other specific mechanical and durability parameters of Concrete

What defines Concrete Performance??

- Is it just with achieving high compressive strength?
  - **Yes and No**

- It is greatly explored and established that conventional concrete is an inherently durable material and its performance improves with increase in compressive strength.

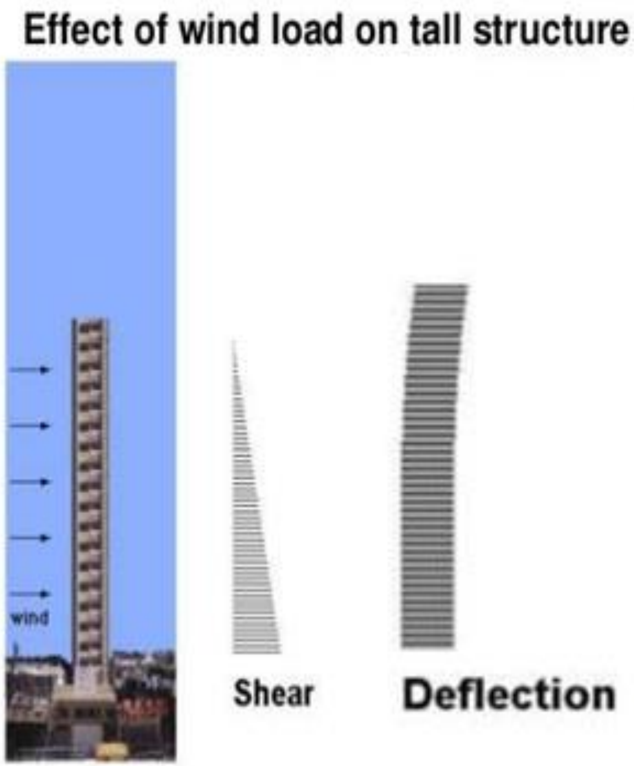
- But in case a HSC, the performance is decided by each and every material components that is used in making it.

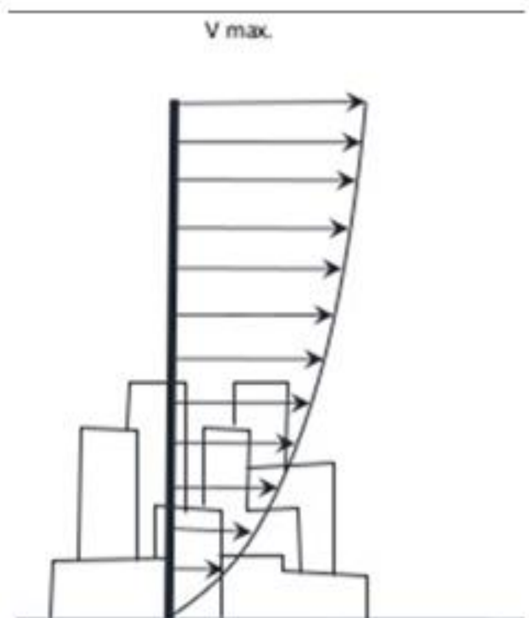
Why HSC/HPC.?

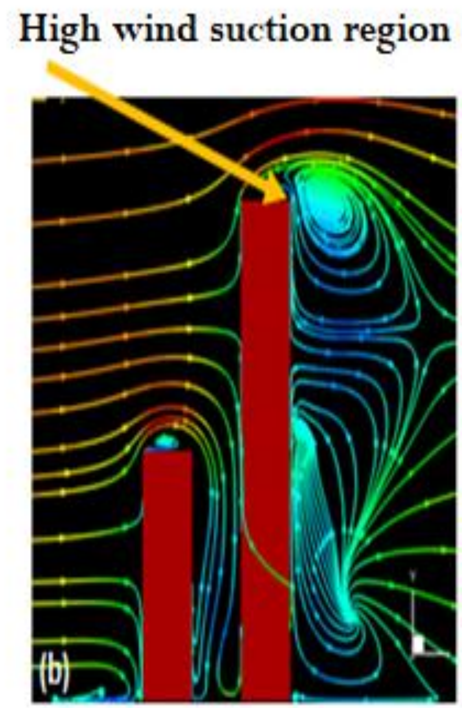
- Changing Construction practices
- Challenging Situations for Concrete
- Faster production cycle
- Durability under severe conditions
- Longer service life
- Maintenance

Importance of Performance criterions of HSC

In High rise buildings >> Heavy loads on foundation and Greater wind loads and suction at higher points





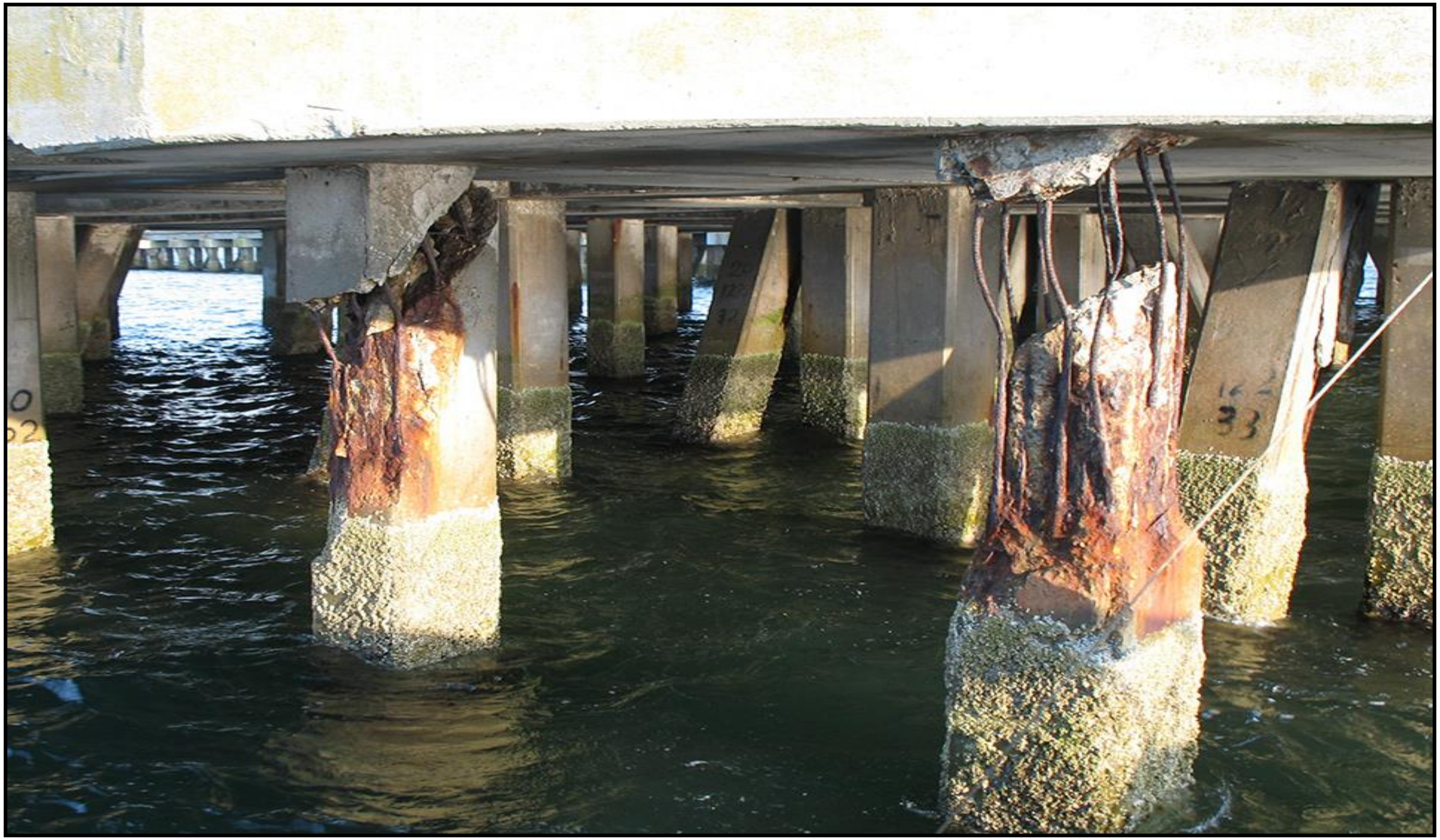


<u>Performance attributes</u>: High Compressive strength paired with MOE for deformation resistance against sway.

Exploitation of concrete infrastructure with unexpected load variations/ natural calamities

<u>Performance attributes</u>: High Compressive strength and Ductility

Concrete Fatigue paired with severe environment exposure



Performance attributes: High Compressive strength, flexural/tensile strength and impermeability against external agents.

R.V.Ranganath, BMSCE.

Comparison of Concrete Variants

	Normal concrete	High-performance concrete		
		High strength	Very high strength	Ultra-high performance concrete
Grade strength by cube (MPa)	≤ 50	55 - 80	85 - 120	> 120
Water/cement ratio	≥ 0.45	0.30 - 0.45	0.25 - 0.30	0.15 - 0.25
Chemical admixtures	Not required	Superplasticizer	Superplasticizer	Superplasticizer
Mineral admixtures	Not required	PFA/GGBS	Silica fume	Silica fume/Nano material
Chloride permeability (Coulombs)	> 2,000	500 – 2,000	100 – 500	≤ 100
Tensile strength (MPa)	Not required	Not required	Not required	≥7
Sustained tensile strength (MPa)	Not required	Not required	Not required	≥5

Modified from Büyüköztürk, O. and Lau, D. High Performance Concrete: Fundamentals and Application, Massachusetts Institute of Technology, Cambridge, Massachusetts, U.S., 2002.

Performance Benefits of HSC..

- Resists high working loads that cannot be resisted by conventional concrete
- Increased strength per unit weight and unit volume
- Increased MOE which increases stability and reduces deflection.
- Flow able Concrete due to more Cementitious phases.
- Better particulate packing and higher impermeability thereby by greater durability.
- Size reduction in final concrete elements with reduced dependency on steel for reinforcement.

What are the Road Blocks?

- Availability of Raw materials
- Consistency in making HSC commercially
- Performance evaluation standards
- Cost of Production.
- Reluctance of Designers
- Demand for High rise buildings in Urban landscape.

Ingredients for HSC

- Same materials as in Conventional Concrete but with an engineered proportions.
  - Cement
  - Aggregates
  - Water
  - Mineral Admixtures
  - Chemical Admixtures
  - Fibers
  - Ultra fine/ Nano additives

For performance based HSC

-Cement

- Cement composition and fineness is crucial to achieve HSC
- 53 grade OPC is more suitable in achieving HSC.
- Also low C_3A cements are preferable
- Special cements like Sulphate resistant cement, RHPC, LHPC can also be used in production.
- A higher OPC content cannot always lead to higher strength and hence demands addition of SCMs.

ACI COMMITTEE REPORT

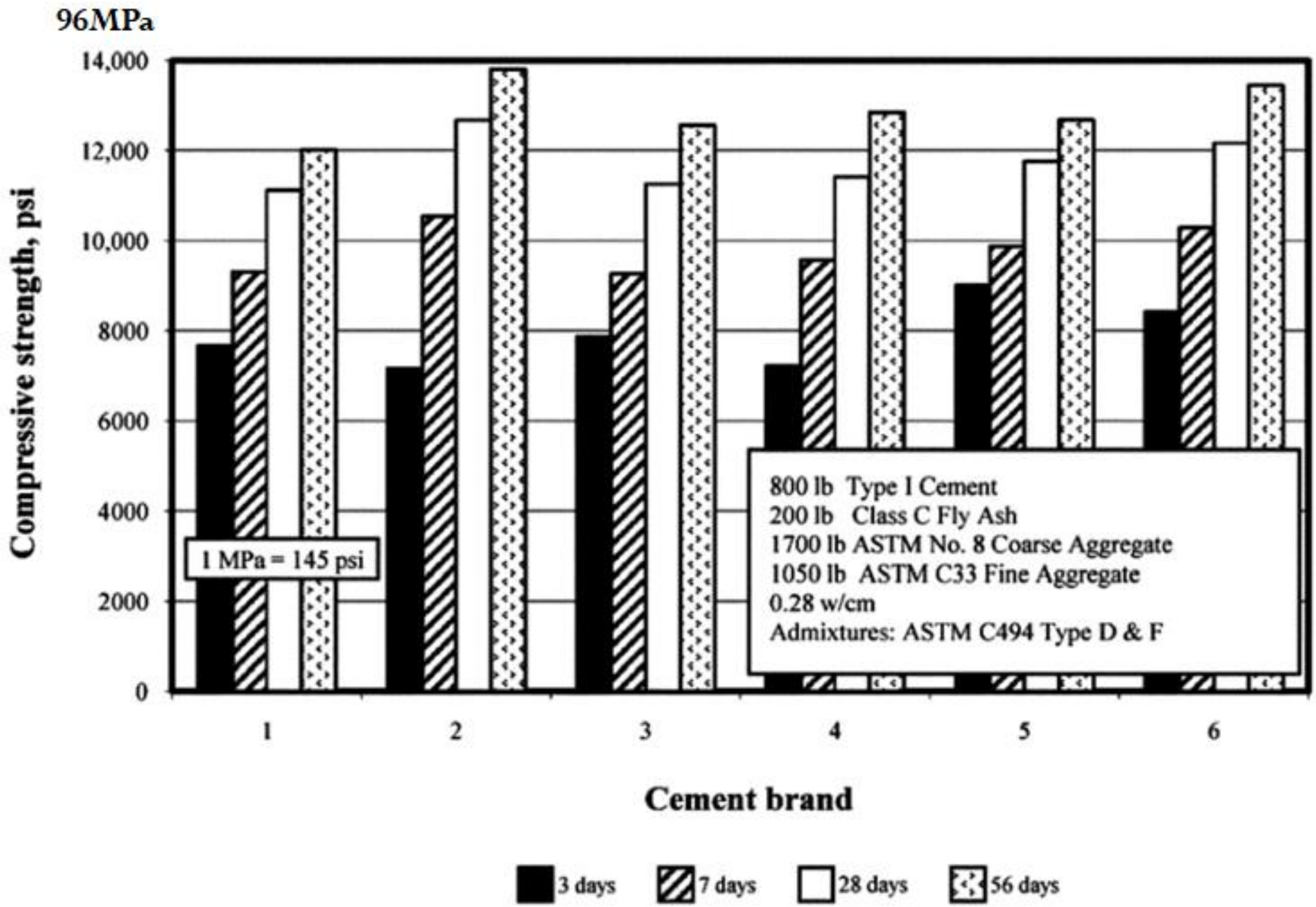


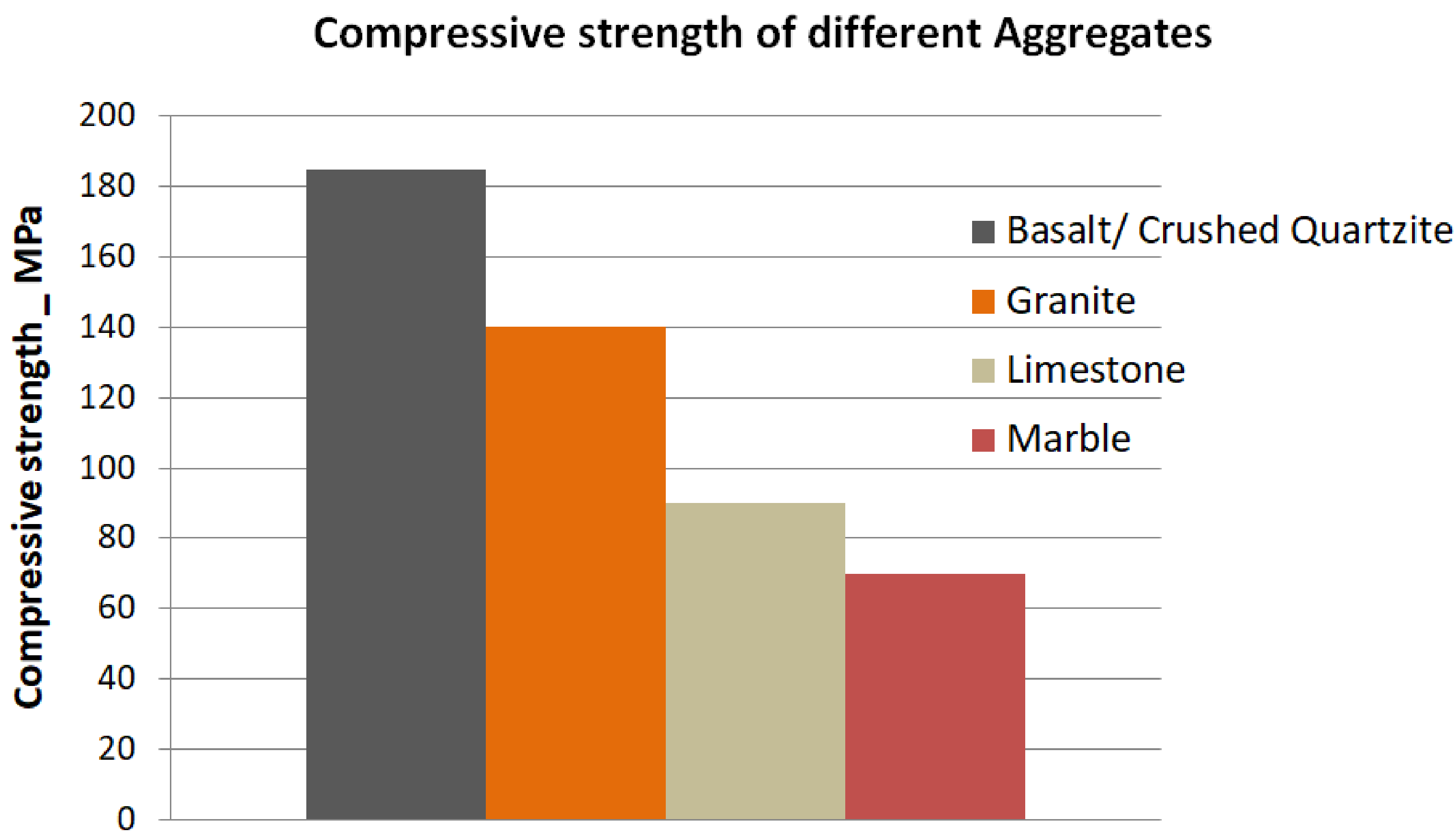
Fig. 4.1—Effects of various brands of cement on concrete compressive strength.

-Aggregates

- Aggregates can both improve and limit the property of HSC depending on their physico-chemical properties.
- Gradation and proportioning of Fine and Coarse aggregates is equally important.
- Maximum aggregate size is usually 12mm and can be less than 8mm based on required concrete parameters.
- However, Researchers have successfully produced strength greater than 100MPa with 20mm downsize aggregates.
- High-strength concretes have been produced using blends of manufactured and natural fine aggregates.
- IS 10262-2019 – Similar guidelines…..

<u>Aggregate shape</u>, an important contributor

Aggregate strength is crucial as well



(Modified from Ke-Ru Wu Et al., Cem. and Conc. Research 2001)

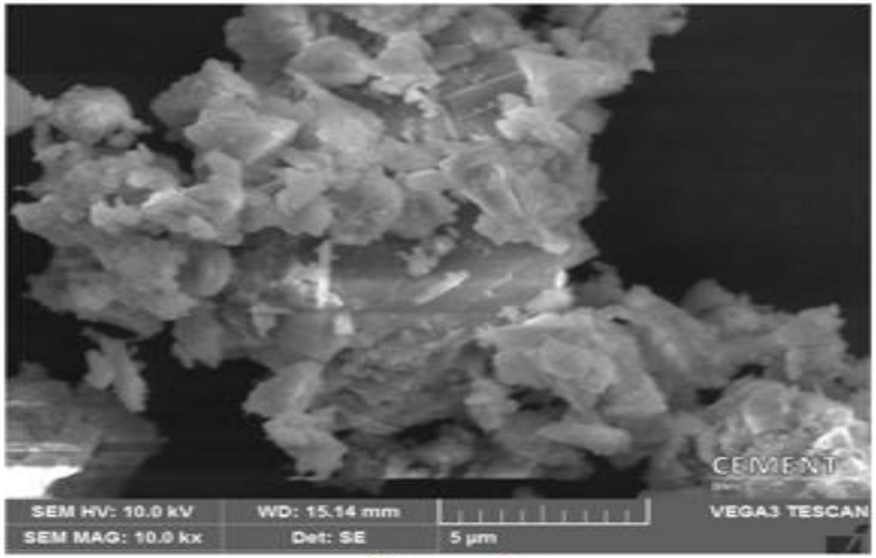
-Mineral Admixtures

- Very much essential to convert Normal Concrete into HSC and *to evolve HSC into HPC*.
- Silica fume, GGBS, Fly ash, Metakaolin, RHA and other natural pozzolans can be used.
- They can act as carbon footprint reducers as well as workability/duarbility enhancers.
- The recommended Cementitious material content is in the range of 400 to 600kg/m^3 for HSCs. (NRMCA report, CIP 33)

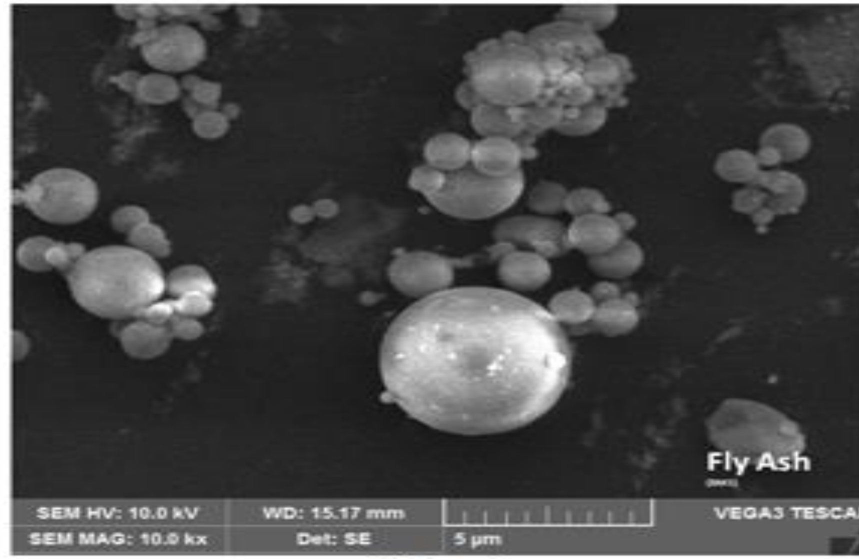
Common Mineral admixtures used in HSC

[Source: National Ready Mixed Concrete Association (NRMCA)]

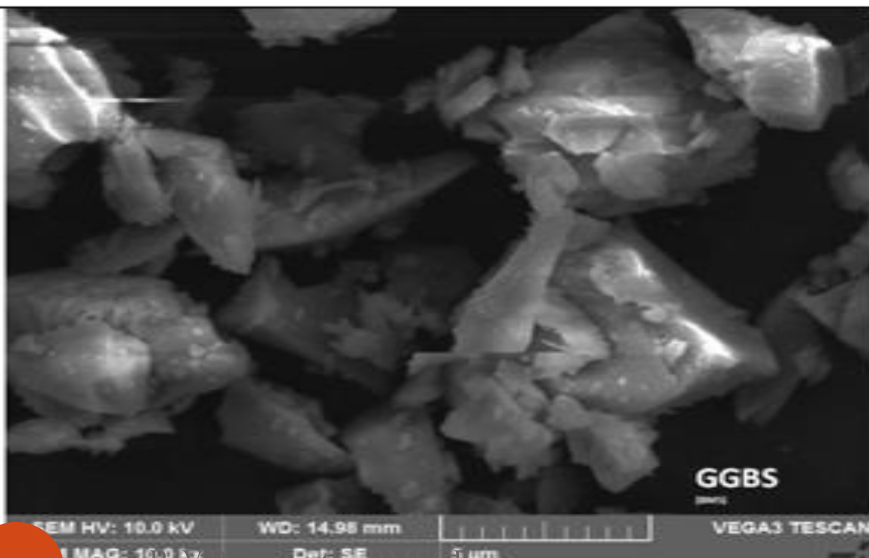
SEM profiles of Cementing materials



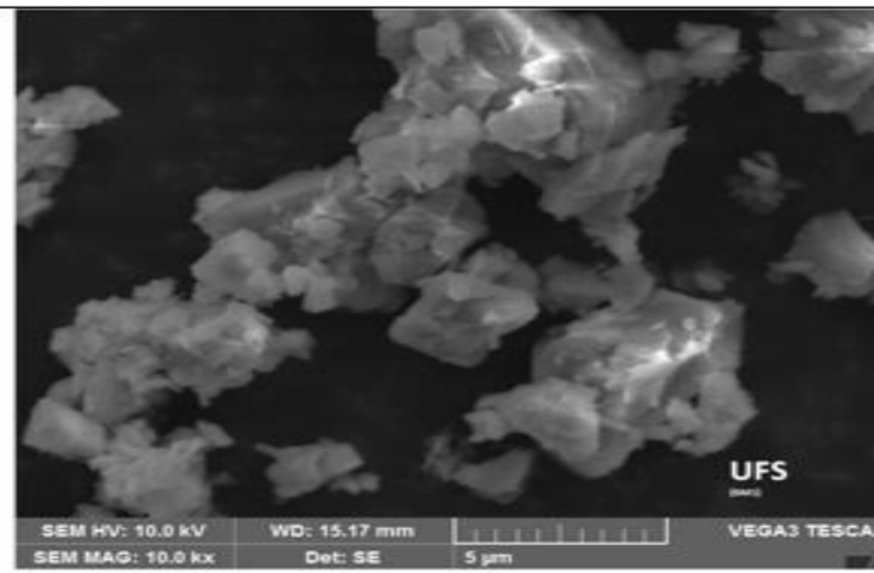
Cement



Fly ash



GGBS

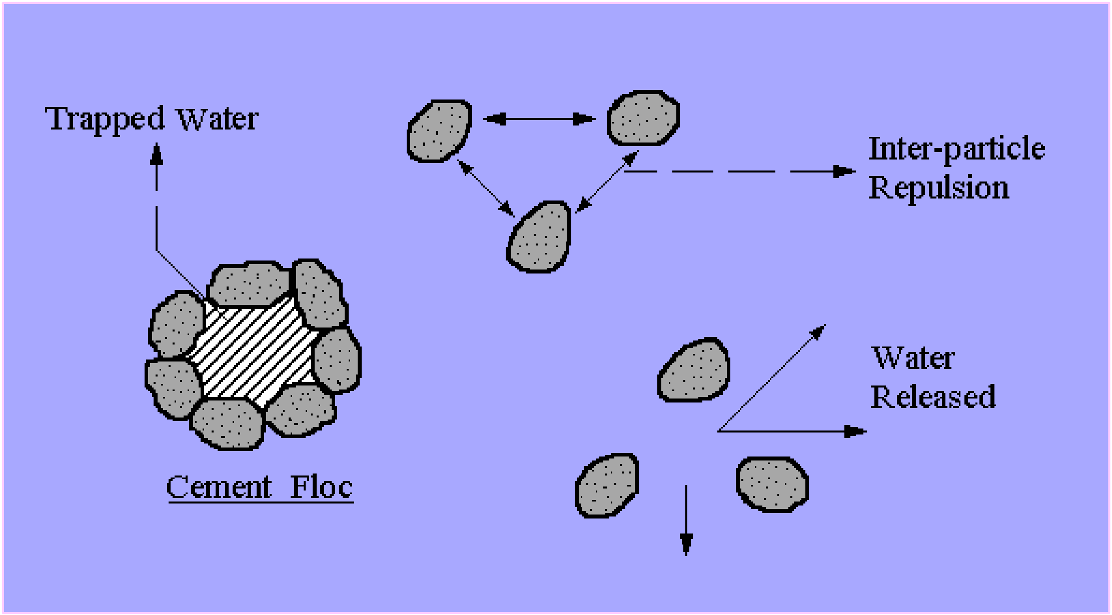


UFS

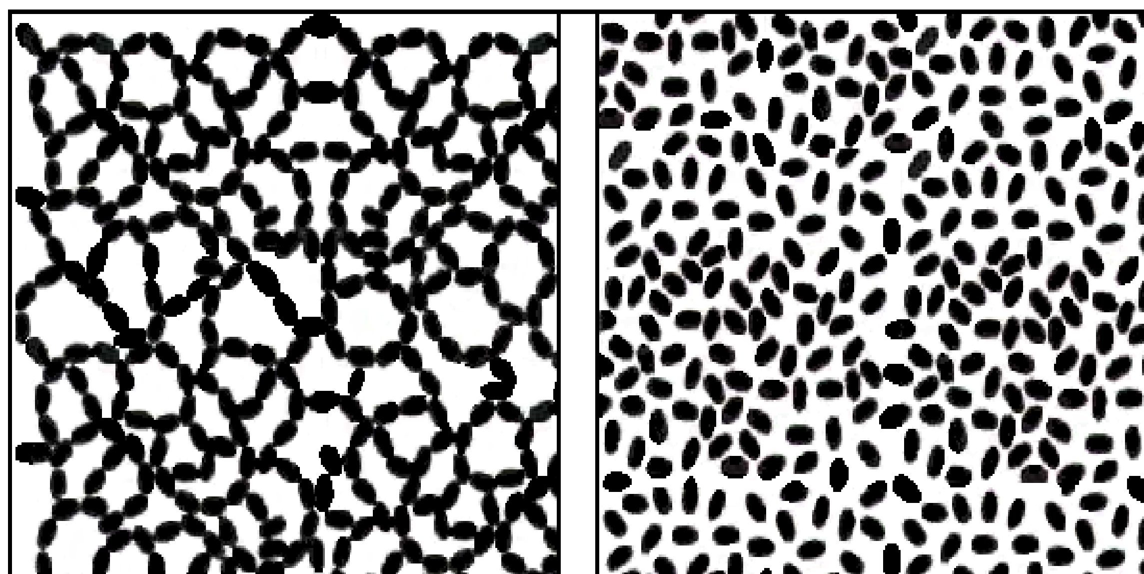
-Chemical Admixtures

- Super plasticizers, VMAs and retarders are most common chemical admixtures used.
- While HRWRA results in lowering water to binder ratio, VMAs and Retarders helps in maintaining a workable mix till the point of execution.
- A high dosage of chemical admixtures greater than 2% of binder content is also acceptable depending on the workability required
- With the addition of super plasticizers, concrete can be successfully produced and placed with a water-to cement ratio as low as 0.2.

Working mechanism of super plasticizers

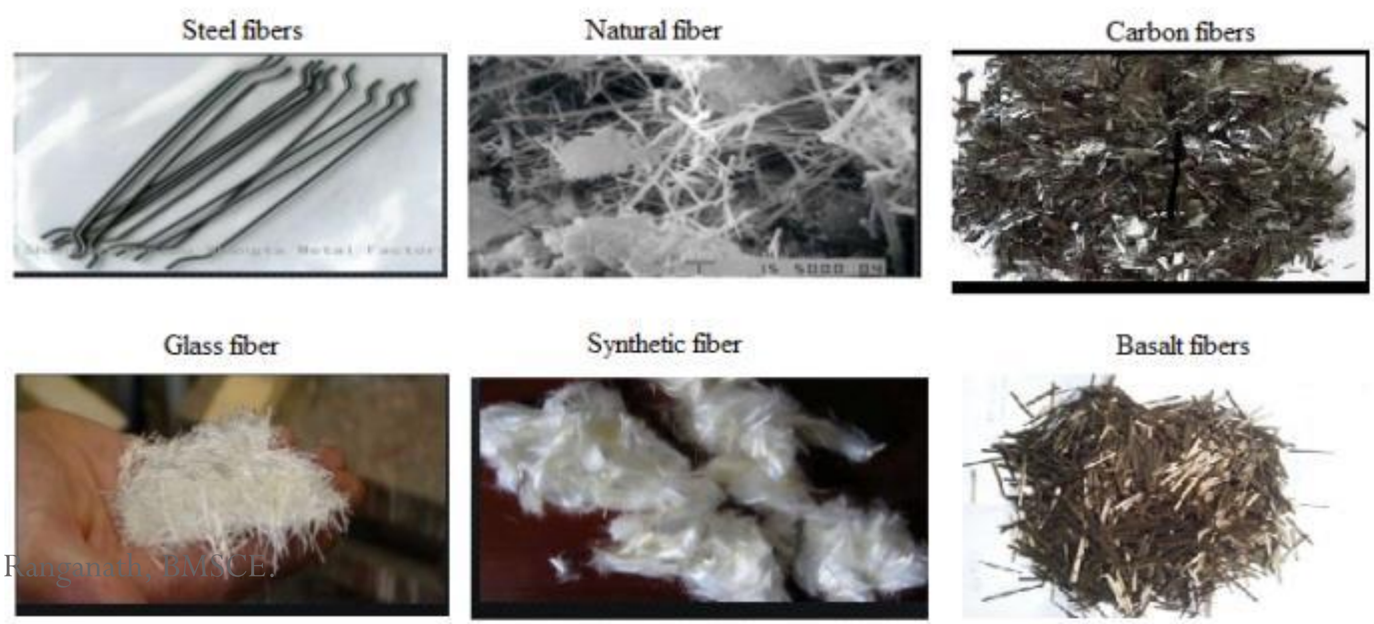


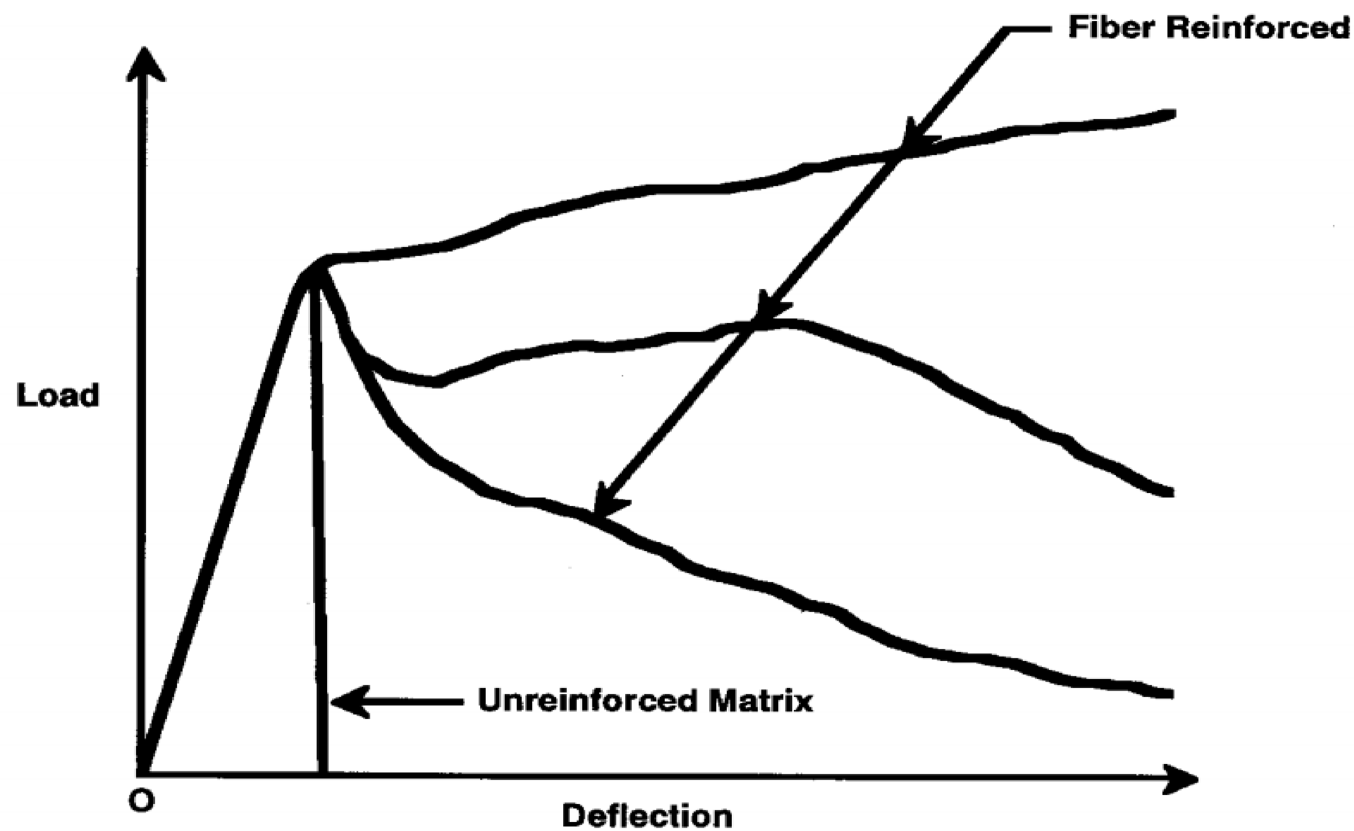
De-flocculation of cement grains in the presence of super plasticizer.



-Fibres

- As the strength increases with high paste content, the brittleness of the concrete also increases.
- In order to enhance the material properties such as flexural toughness and crack resistance of the concrete and to control the brittle failure, certain small, discrete fibres are added to concrete in its fresh state

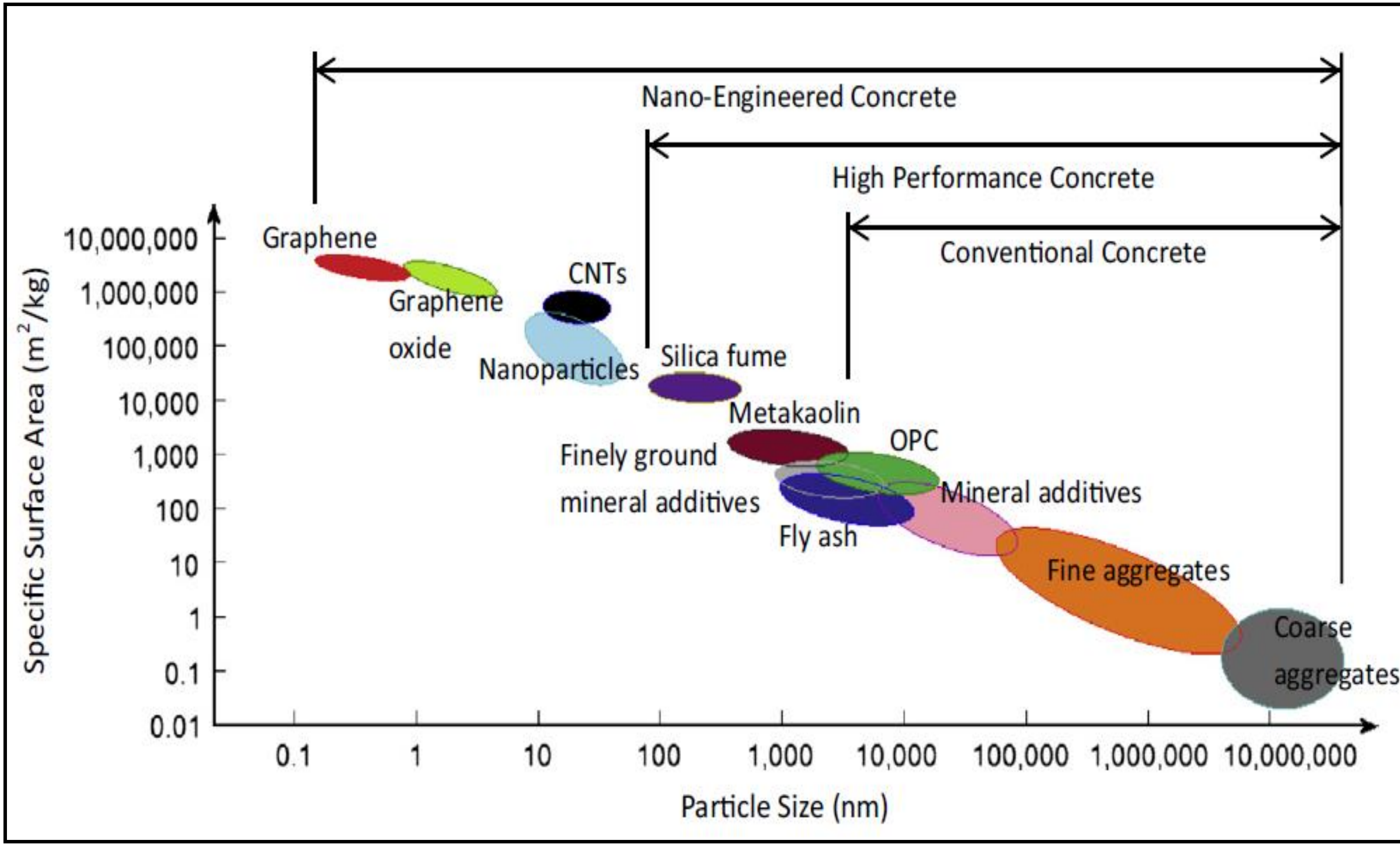




Typical post-cracking behaviour of Fibre added Concrete [ACI 544.1R-96]

Nano additives:

- Ultra fine additives (reactive/ inert) with particle size in the range of micron to nano level are found to be useful in enhancing performance of HSC.
- Nano Silica, the most explored admixture is found to result in high early strength with a greater pozzolanic activity.
- Ultra fine Cabon additives such as Graphene Oxide has shown promising enhancement in HSC performance.
- Nano fibres such as CNTs are capable of arresting micro cracks and their propagation very effectively and contribute to overall performance of Concrete.



Specific Surface areas of different concrete additives

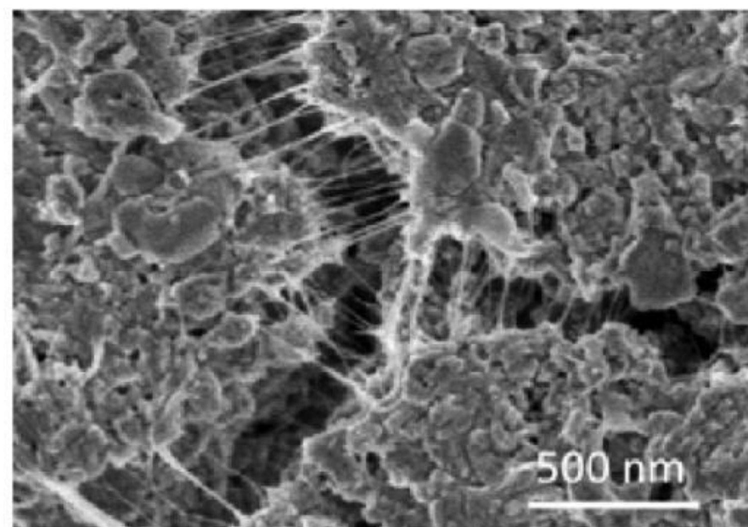
(American Ceramic Society Bulletin)

Dense micro structure in Nano silica added Concrete

(BMSCE, Bengaluru)

Crack bridging by CNTs

(**N.B. Singh et al.,** Materials Today: Proceedings 4,2017)



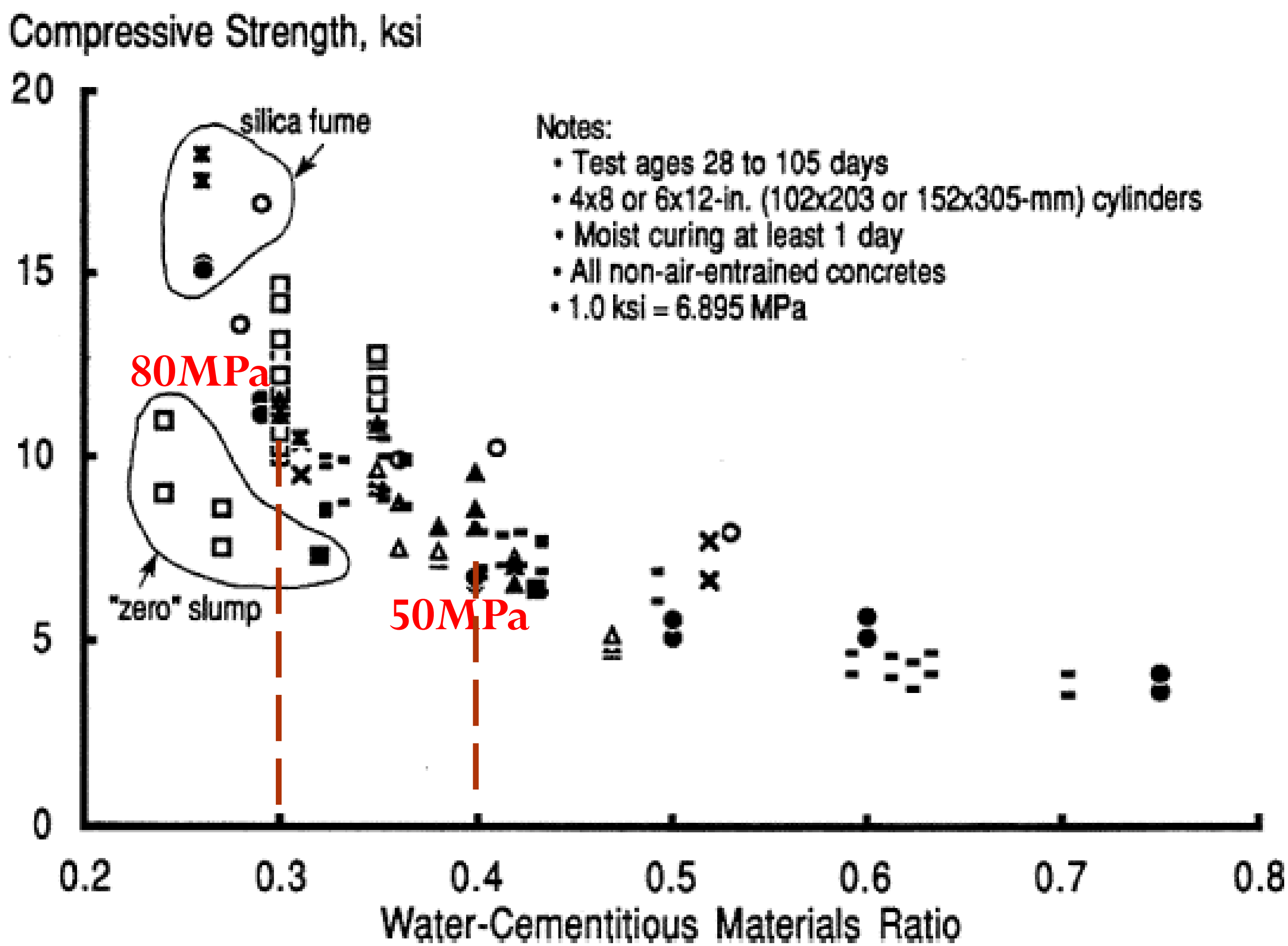
What are the Road Blocks?

- **Availability of Raw materials**

  - **Most of the ingredients for HSC are available commercially in India now.**

Proportioning techniques for HSC

- **Lower water to binder ratio**
  - Backed by Duff Abrams law
  - Use of Chemical admixtures
  - For HSC/ HPCs water binder ratio is generally in the range of 0.23 -0.35
  - However, it is necessary to establish an optimum w/b ratio to avoid excess dependency on chemical admixtures which can create variations in desired concrete parameters.
  - Proper compaction is an important factor to attain HSC at low water content.

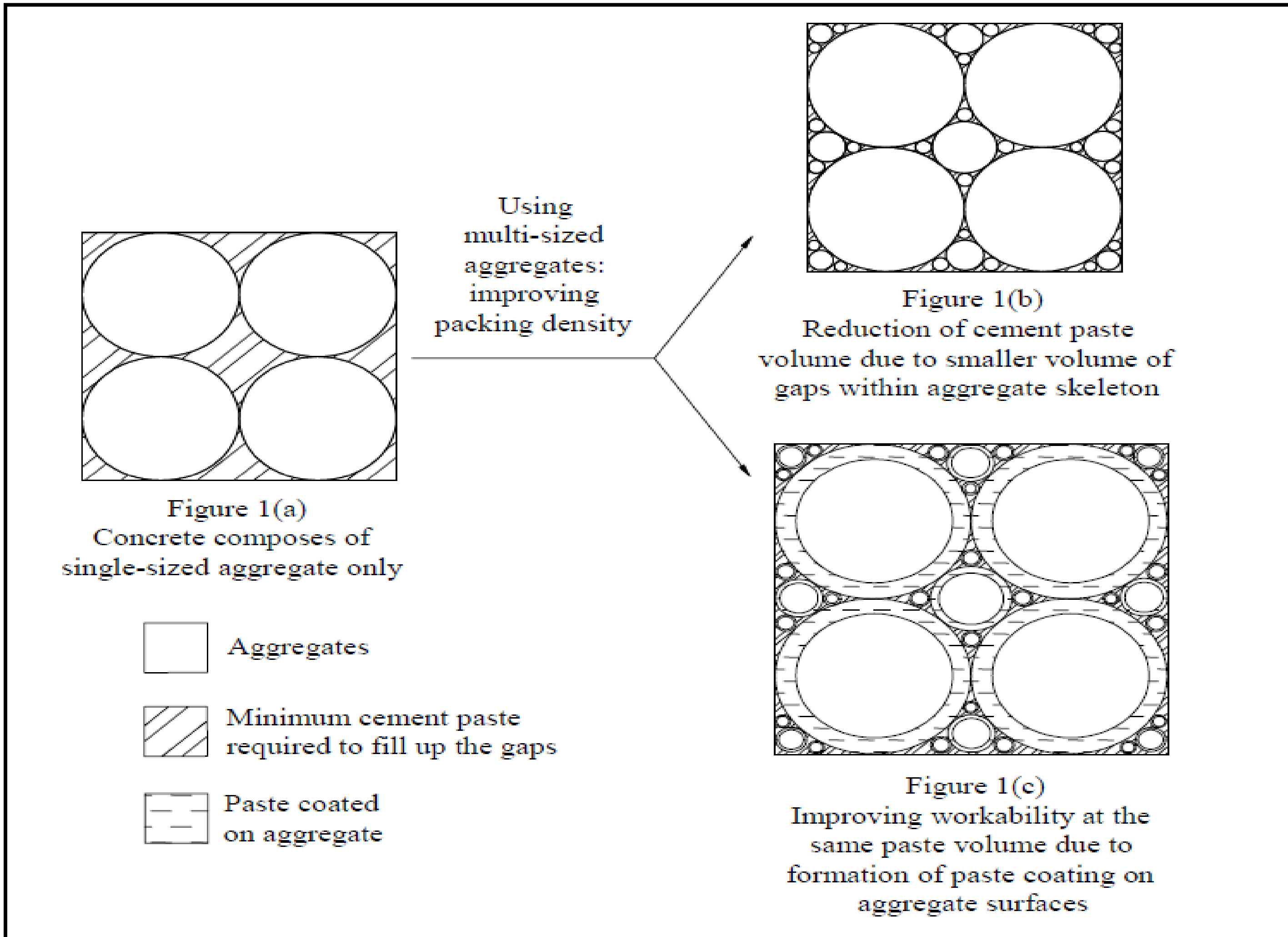


Compressive Strength, ksi
20
15
10
5
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Water-Cementitious Materials Ratio
silica fume
"zero" slump
80MPa
50MPa
Notes:
• Test ages 28 to 105 days
• 4x8 or 6x12-in. (102x203 or 152x305-mm) cylinders
• Moist curing at least 1 day
• All non-air-entrained concretes
• 1.0 ksi = 6.895 MPa

- **Particle/ Aggregate packing approach**

  - A simple approach to attain a proportion of aggregates with least void content.
  - Aggregate gradation and shape is an important factor
  - Improper proportioning of aggregates can result in too much of voids which demands for higher paste content and become potential site for capillary pores during the hardening process of Concrete.

- The basic concept of adding fine particles into the concrete mix is based on packing theory. *It is found that packing density of concrete governs the performance of concrete to a large extent.*



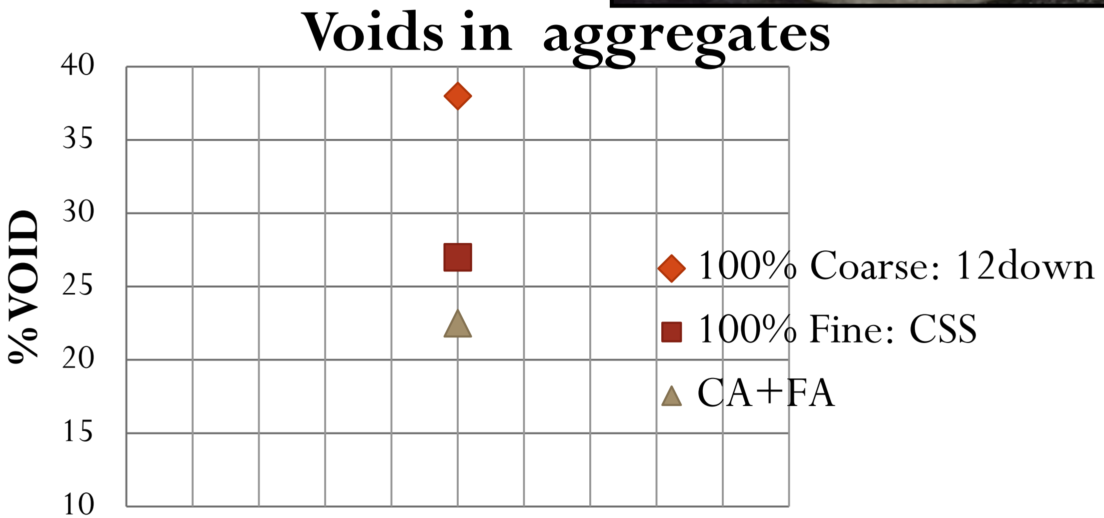
❖ **Consider a blend of particles of different sizes**.

- When mixed together the gaps between the larger particles are filled up successively by smaller size particles.
- If the filling up process is extended infinitely by incorporating particles of extremely fine size, all the voids can be filled up by solid particles, leading to a packing density very close to 1.
- **Yet**, due to practical limit to the size range and shape of the particles there is always some voids remaining unfilled.(Kwan and Mora 2001)

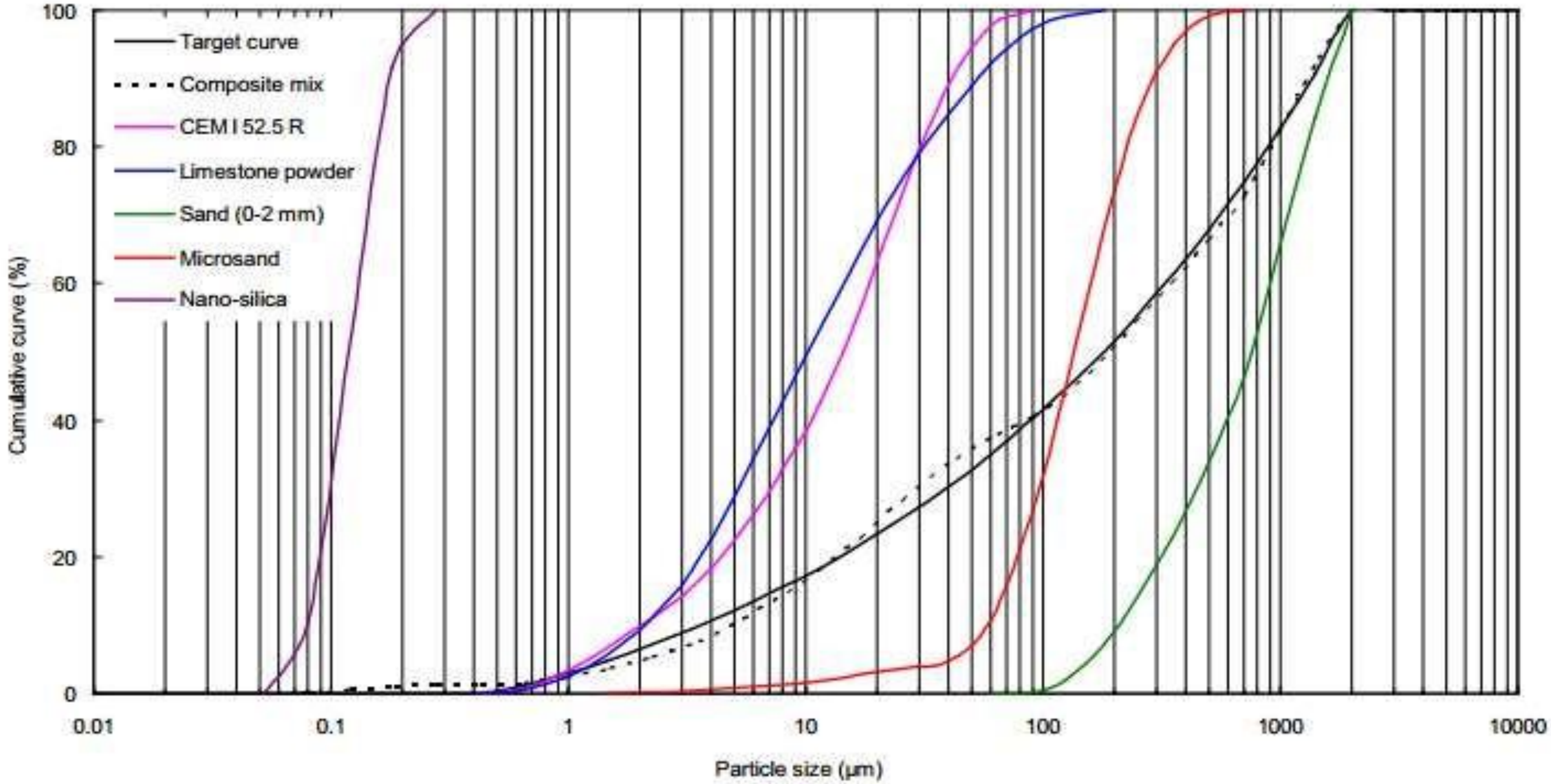
Only Coarse Agg : 38% voids

Only Fine Agg : 27% voids

Combined : 23% voids



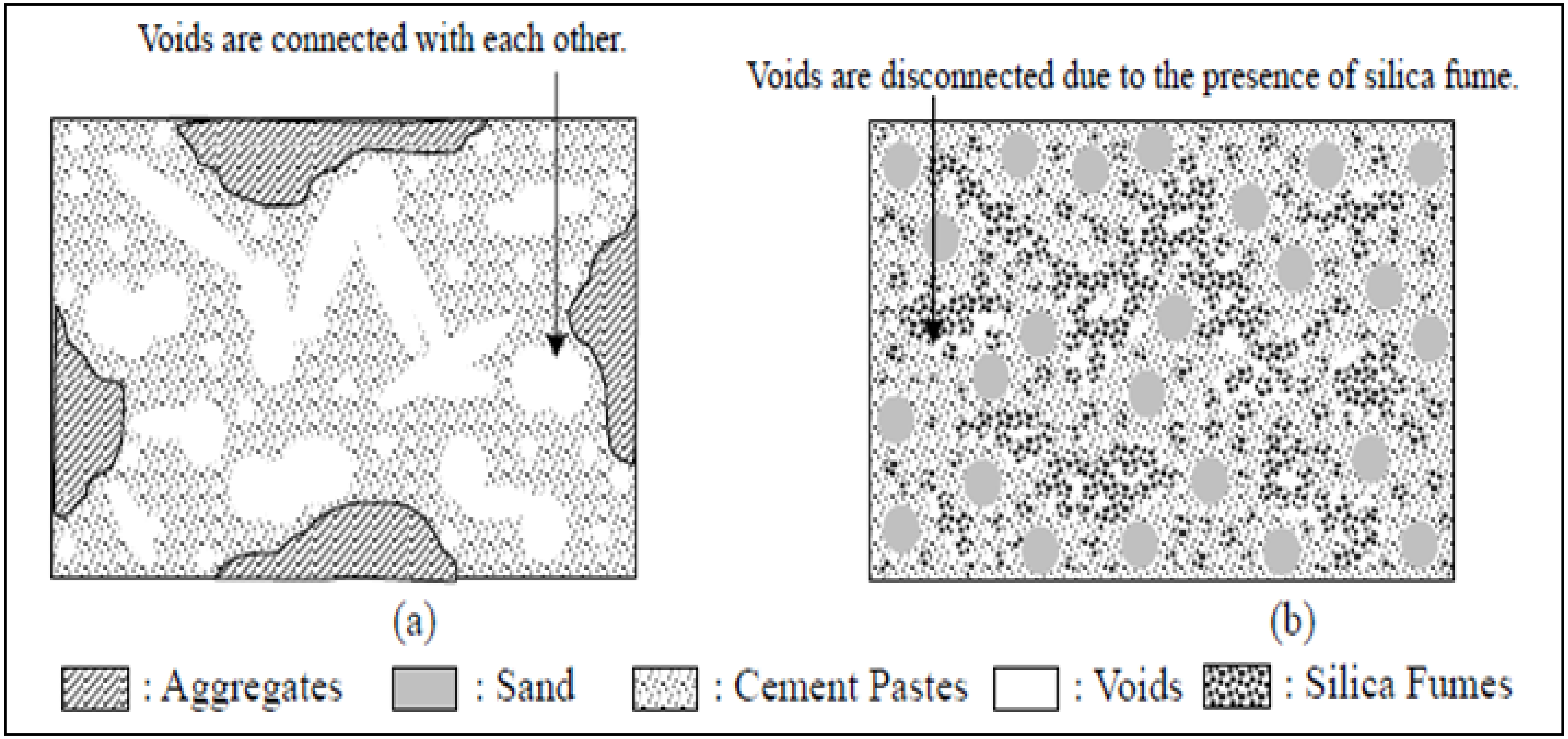
(Data from Research works, BMSCE, Bengaluru)



Particle size distribution of different ingredients involved, the target curve and the resulting integral grading curve of the mixtures.

Paste densification

- Achieved by increasing the paste volume of concrete
- HSC/ HPC can be realized for paste volume of greater than 32% unlike conventional concrete which has higher aggregate volume
- OPC aided with mineral admixtures at different combinations have successfully resulted in satisfactorily increasing the paste phase in concrete.



Pore connectivity in paste: (a) Normal Concrete (b) HSC

(Ref- **Oral Büyüköztürk and Denvid Lau, "High Performance Concrete: Fundamentals and Application"** Department of Civil and Environmental Engineering, Massachusetts Institute of Technology.

Mixing with Powders.

- Normal mixing methods (Pan and drum mixers) can result in poor and non uniform distribution of powder materials (SCMs) at a lower w/b ratios thereby bringing down the mix efficiency.

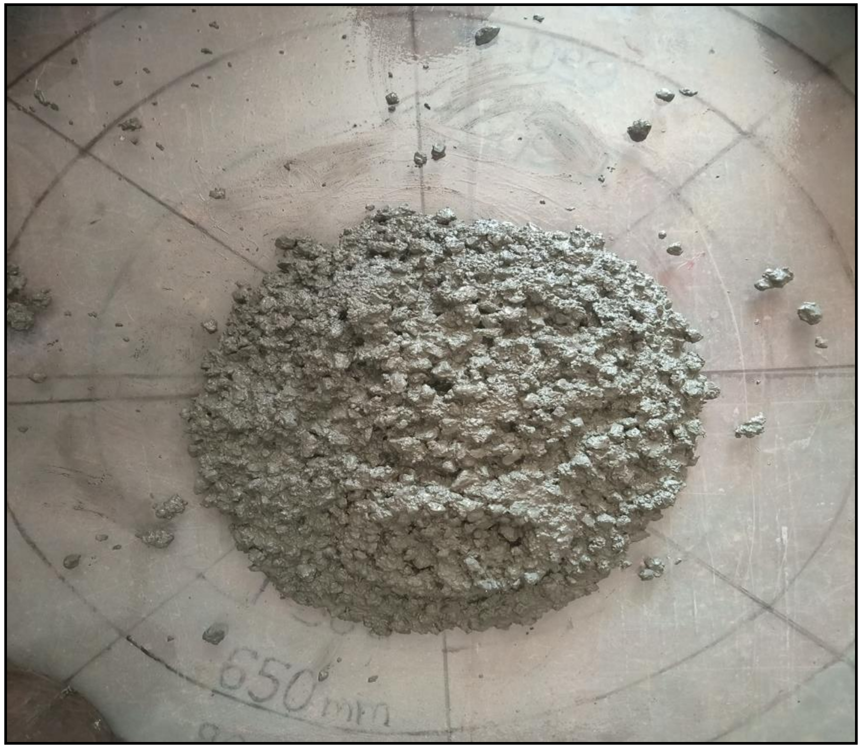
- Also **at normal speed** a **high duration of mixing** (more than 15mins) **is required** to attain certain uniformity.

- The above reasons demand for special mixing techniques involving high speed mixers.

- Mixing at high speed enhances the uniformity of distribution of ultra fine additives even at w/b ratios less than 0.25.

Pan Mixer – 30 to 40rpm

High Speed Mixer – >500rpm



Pan Mixed Concrete (360mm spread)

High speed Mixed Concrete (520mm flow)

For same mix with only mix speed variations- 40 to 50% flow increment.
Strength is also observed to increase by 15 to 20% at early age

-BMSCE, Bengaluru.

IS 10262:2019 Recommendation

SECTION 3 HIGH STRENGTH GRADES OF CONCRETE

6 HIGH STRENGTH CONCRETE (GRADE M 65 AND ABOVE)

High strength concrete is the concrete that has characteristic compressive strength of 65 N/mm^2 or more. This section provides the guidance for selecting mix proportion for M65 or above.

Usually, for high strength concrete mixes specially selected cementitious materials and chemical admixtures, that is, super plasticizers are used, and achieving a low water–cementitious materials ratio (w/cm) is considered essential.

The procedure for proportioning high strength concrete is similar to that required for ordinary/standard strength concrete. The procedure consists of series of steps that, when completed, provide a mixture meeting workability, strength and durability requirements based on the combined properties of the individually selected and proportioned ingredients.

6.1 Materials

IS 383. Generally, for high strength, a fine aggregate of coarser size is preferred (Zone I or Zone II), due to availability of high fines content from the cementitious materials.

6.1.4 *Chemical Admixtures*

High strength concrete mixes usually have a low water-cementitious materials ratio (w/cm). These low w/cm ratios are generally only attainable with high-range water-reducing admixtures (HRWRA). PCE type (Poly carboxylate ether based) super plasticisers which reduce water content by 30 percent or above at appropriate dosages, maybe used.

6.2 Concrete Mix Proportioning

6.2.1 *Target Strength for Mix Proportioning*

See **4.2**.

6.2.2 *Selection of Maximum Size of Aggregate*

Based on the strength requirement, the maximum size of aggregates is generally restricted to 20 mm; however, for grades M80 and above, aggregates of maximum size 10.0 mm to 12.5 mm may be preferable.

IS 10262:2019 Recommendation

Table 8 Recommended w/cm for High Strength Concrete made with HRWRA
(*Clause* 6.2.5)

Sl No.	Target Compressive Strength at 28 Days N/mm^2	Water–Cementitious Materials Ratio: Nominal Maximum Size of Aggregate		
		10.0 mm	12.5 mm	20.0 mm
(1)	(2)	(3)	(4)	(5)
i)	70	0.36	0.35	0.33
ii)	75	0.34	0.33	0.31
iii)	80	0.32	0.31	0.29
iv)	85	0.30	0.29	0.27
v)	90	0.28	0.27	0.26
vi)	100	0.26	0.25	0.24

NOTE — The recommended w/cm are for 28 days cement strength 53 MPa and above; for cement of other strength values, suitable adjustments may be made by reducing the w/cm.

Table 9 Recommended Dosages of Mineral Admixtures Materials for High Strength Mixes
(*Clause* 6.2.6)

Sl No.	Mineral Admixtures	Recommended Dosages, Percentage by Mass of Total Cementitious Materials
(1)	(2)	(3)
i)	Fly ash	15 - 30
ii)	Ground granulated blast furnace slag	25 - 50
iii)	Metakaoline	5 - 15
iv)	Silica fume	5 - 10

What are the Road Blocks?

- Consistency in making HSC commercially

  - **Standard guidelines available….**

Some Example HSC Mixtures

A. Regular HSC

- Designed with popular Supplementary Cementitious components at ternary blend level which includes OPC, GGBS/Fly ash and Ultra fine Slag.
- Aggregate proportions optimized at first for least voids
- Paste volume increment is studied with varying the proportions of cementing materials under binary and ternary blends.
- Water and chemical admixtures are maintained constant for mixes.

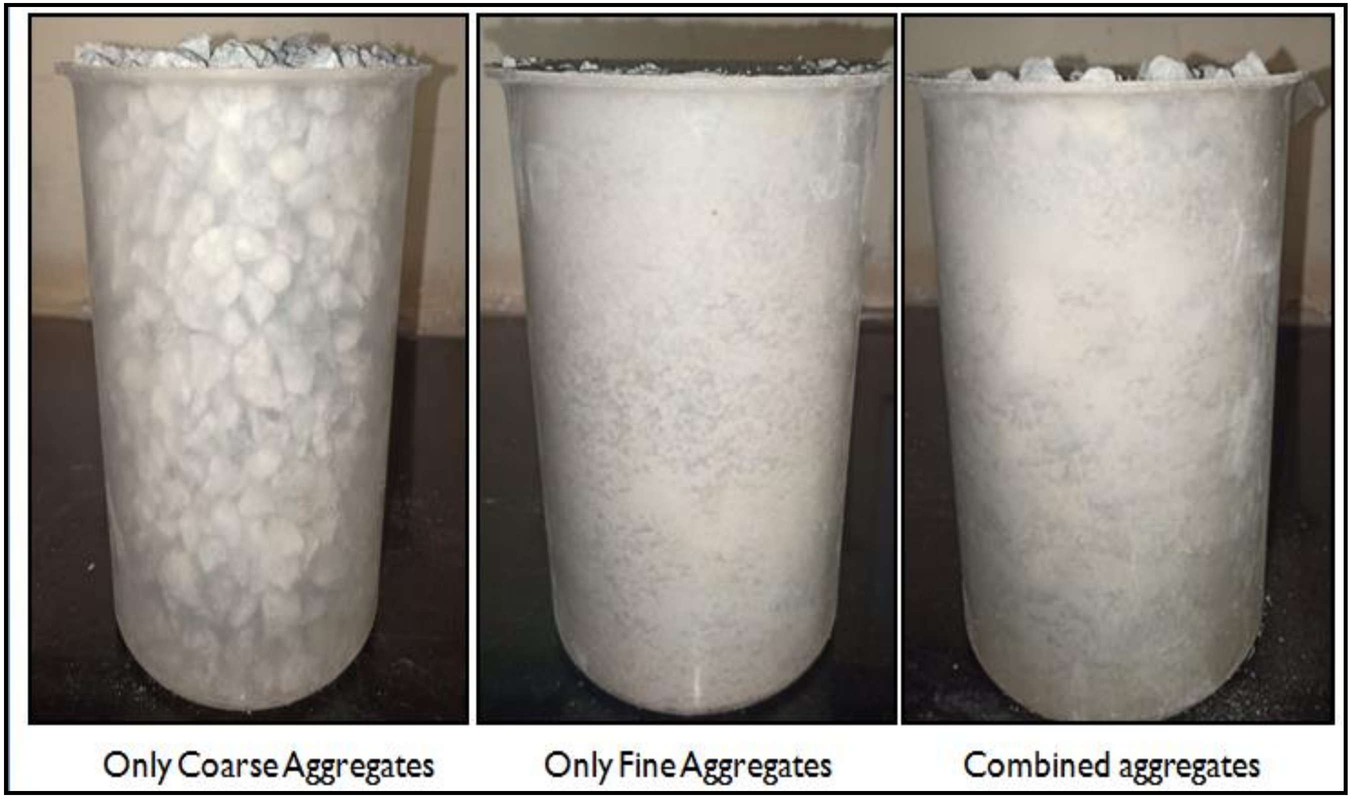
Research Methodology

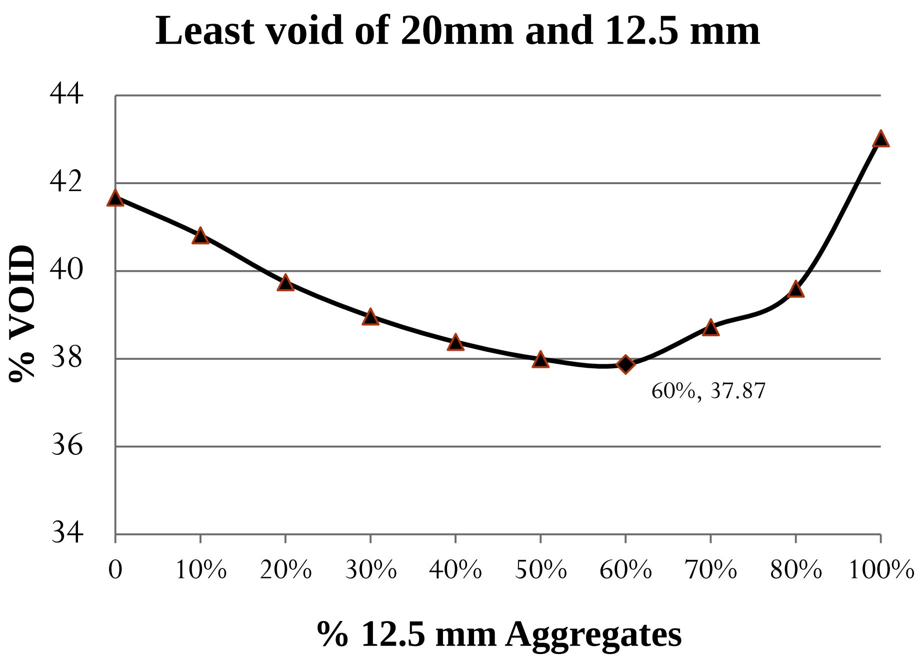
Step 1:

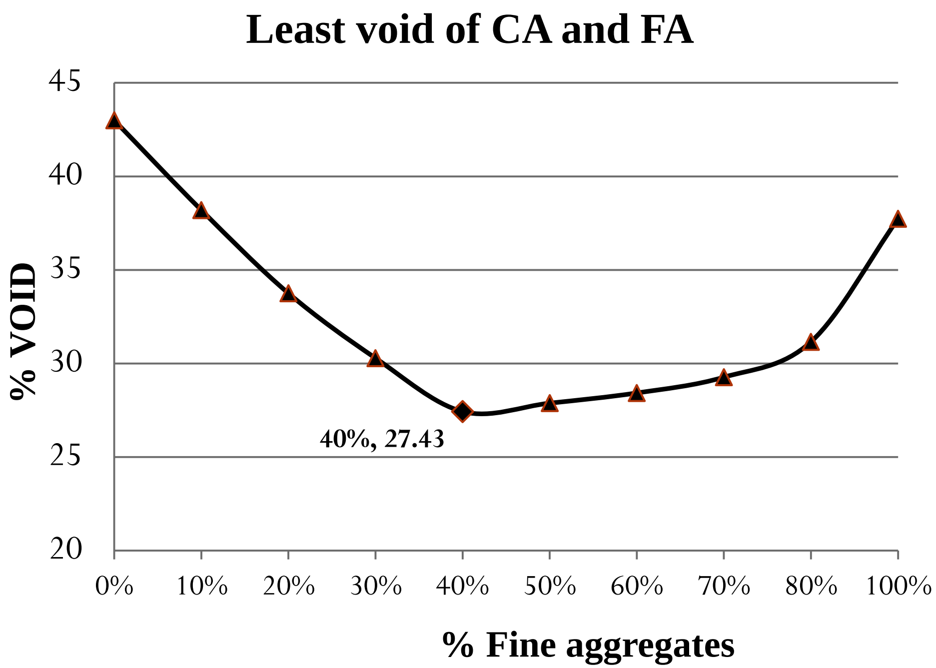
Aggregate packing approach

Step 2:

Paste optimization




Least void of 20mm and 12.5 mm
44
42
40
38
36
34
% VOID
60%, 37.87
0
10%
20%
30%
40%
50%
60%
70%
80%
100%
% 12.5 mm Aggregates

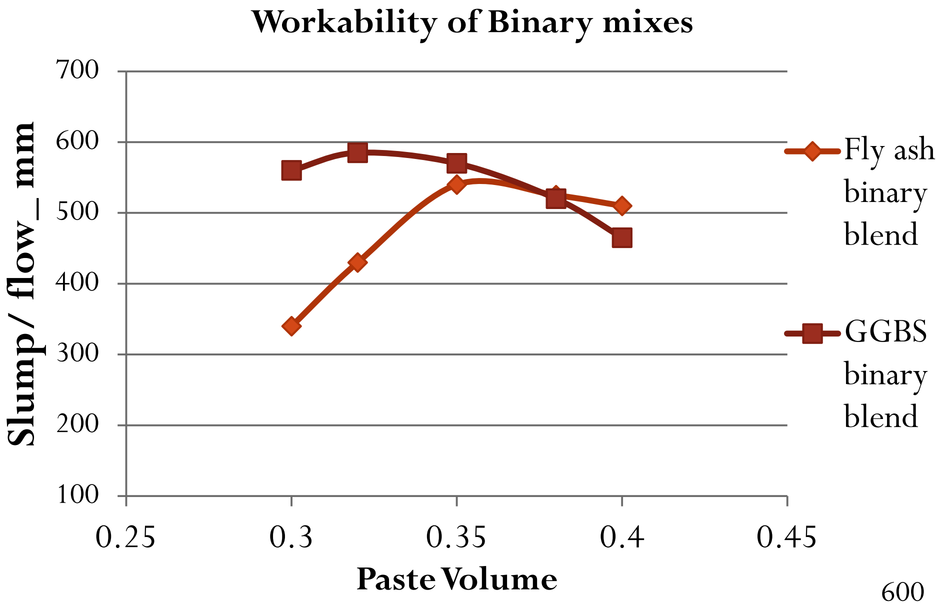

Least void of CA and FA
45
40
35
30
25
20
% VOID
40%, 27.43
0%
10%
20%
30%
40%
50%
60%
70%
80%
100%
% Fine aggregates

MIX RECIPE

	Mix	Vp	OPC kg/m³	Fly ash kg/m³	GGBS kg/m³	UFS kg/m³	Total powder	Water kg/m³	% SP	Volume of Aggregates
Control	CC	0.29	450	-	-	-	450	144	0.3	0.71
SET 1: Fly ash based blends										
	Mix	**Vp**								
Binary blend (OPC+ Fly ash)	CF1	0.3	450	21	-	-	471	144	0.3	0.7
	CF2	0.32	450	78	-	-	528	144	0.3	0.68
	CF3	0.35	450	134	-	-	584	144	0.3	0.65
	CF4	0.38	450	191	-	-	641	144	0.3	0.62
	CF5	0.4	450	236	-	-	686	144	0.3	0.6
	Mix	**%UFS**								
Ternary blend (OPC+ Fly ash+ UFS)	Ref-CF3	0	450	134	-	-	584	144	0.3	0.65
	CFU1	2	450	134	-	9	593	144	0.3	0.65
	CFU2	4	450	134	-	18	602	144	0.3	0.64
	CFU3	6	450	134	-	27	611	144	0.3	0.64
	CFU4	8	450	134	-	36	620	144	0.3	0.64
SET 2: GGBS based blends										
	Mix	**Vp**								
Binary blend (OPC+ GGBS)	CG1	0.3	450	-	29	-	479	144	0.6	0.65
	CG2	0.32	450	-	107	-	557	144	0.6	0.65
	CG3	0.35	450	-	185	-	635	144	0.6	0.64
	CG4	0.38	450	-	264	-	714	144	0.6	0.64
	CG5	0.4	450	-	328	-	778	144	0.6	0.64
	Mix	**%UFS**								
Ternary blend (OPC+ GGBS+ UFS)	Ref-CG4	0	450	-	264	-	714	144	0.6	0.62
	CGU1	2	450	-	264	9	723	144	0.6	0.62
	CGU2	4	450	-	264	18	732	144	0.6	0.62
	CGU3	6	450	-	264	27	741	144	0.6	0.61
	CGU4	8	450	-	264	36	750	144	0.6	0.61

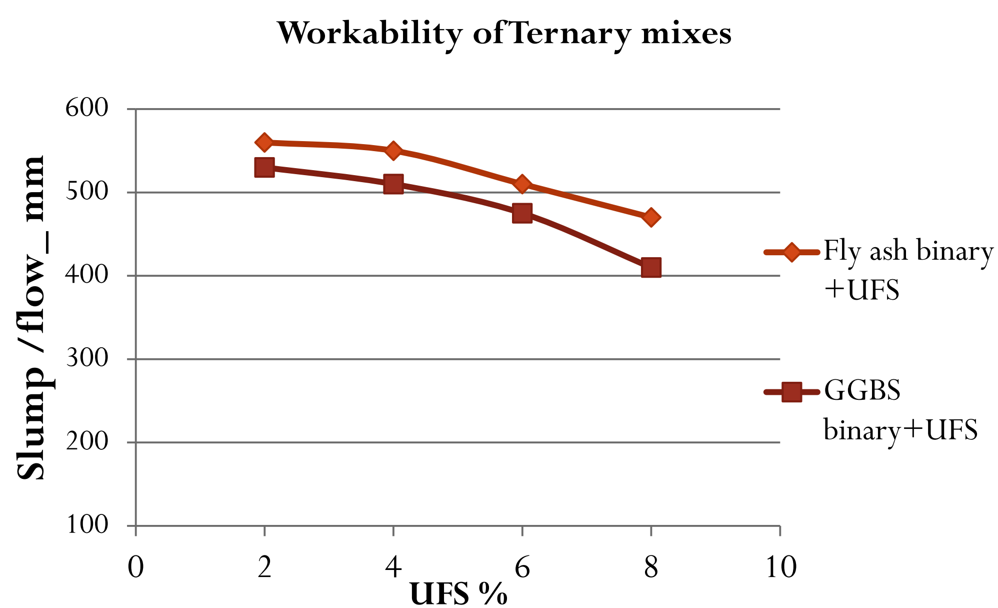
Concrete performance Evaluation

- FRESH PROPERTIES



Flow performance is dependent on type of mineral admixture and its dosage.

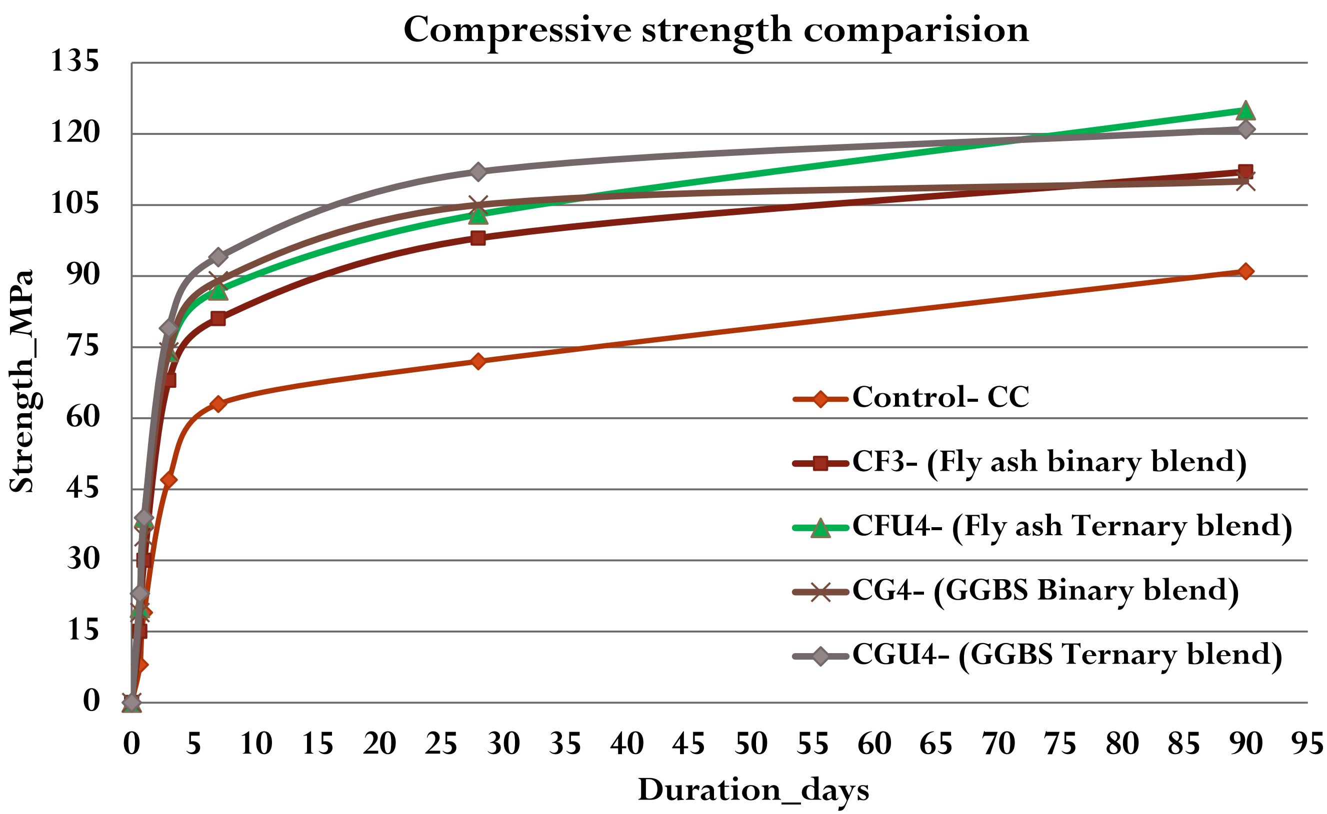
As the blending materials increases for a constant water and super plasticizer dosage, flow of HSC reduces after an optimum level.



R.V.Ranganath, BMSCE.

Concrete performance Evaluation

- HARDENED PROPERTIES



Strength greater than 100MPa can be achieved by 28 days with ternary blends of appropriate cementing materials and aggregate packing approach.

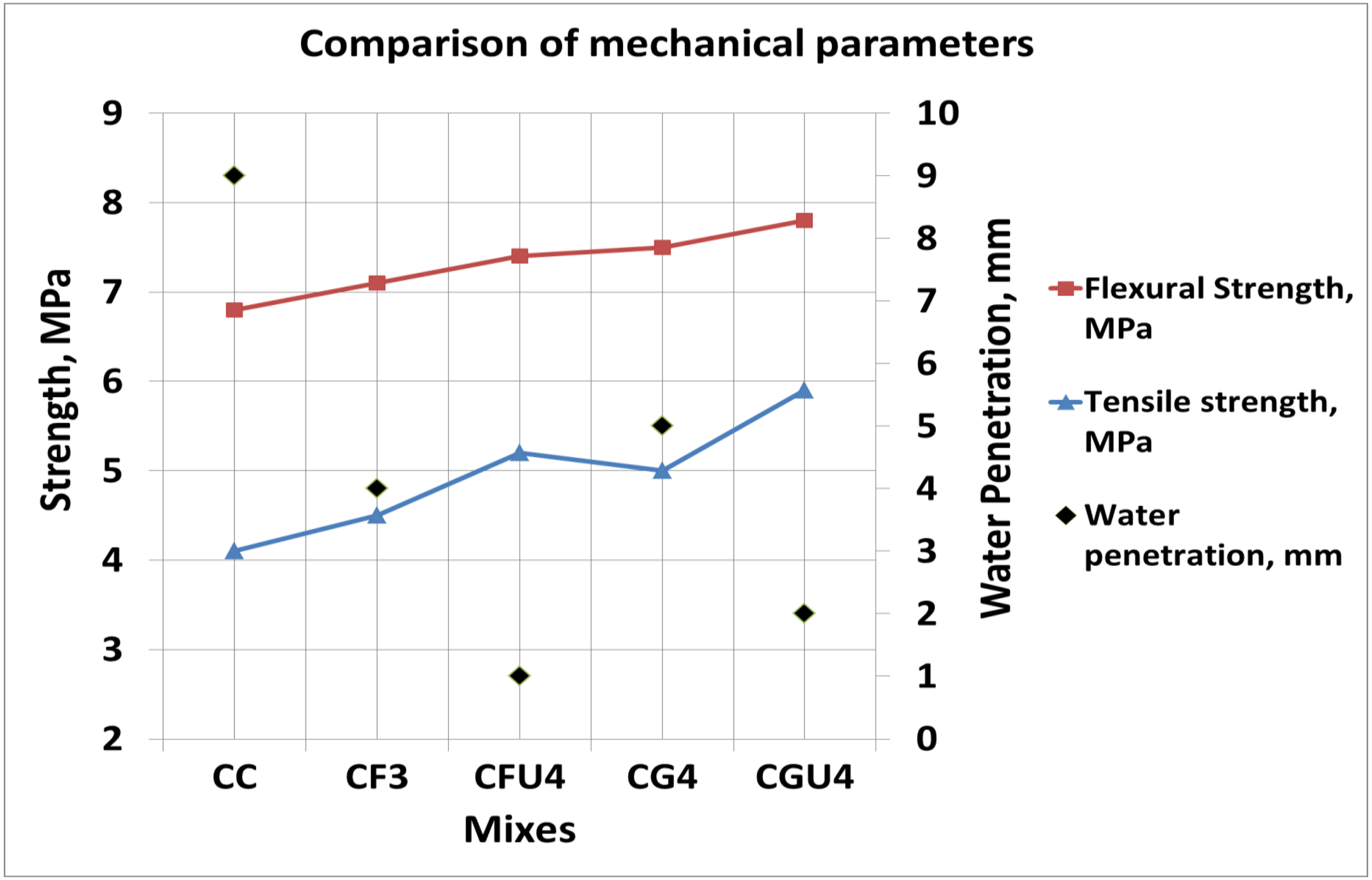
With ternary blend the gain in later day strength at 90days is also prominent.

Early strength in the range of 30 to 35 MPa at 24 hours is also possible.

* UKIERI UCC- 2019

Concrete performance Evaluation

- OTHER MECHANICAL PARAMETERS OF OPTIMAL MIXES

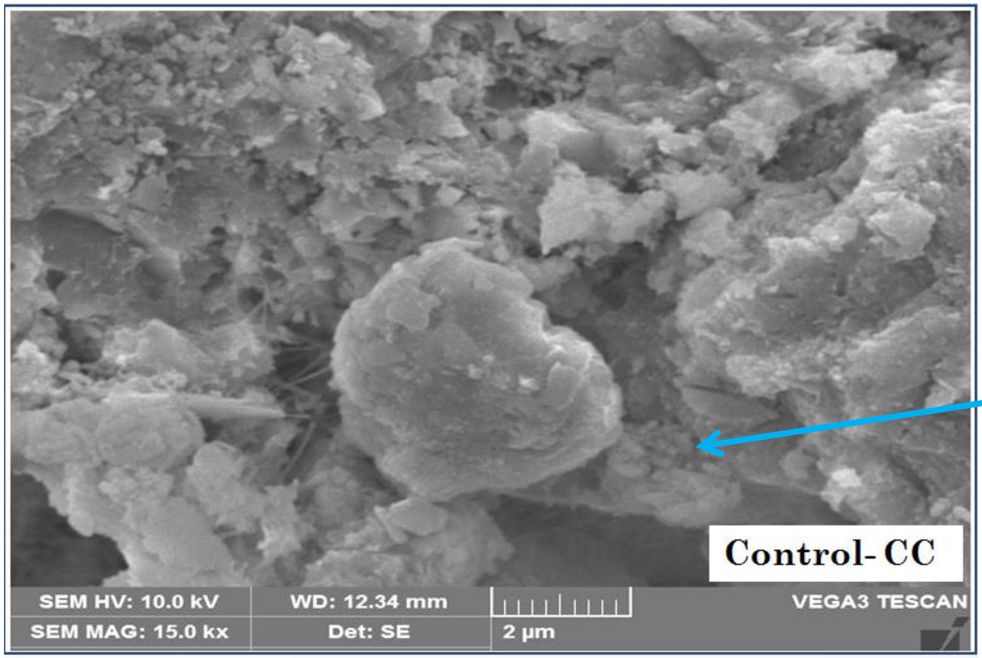


- Enhanced flexural and tensile strength with ternary blends
- Reduced water penetration , thus a better durability performance

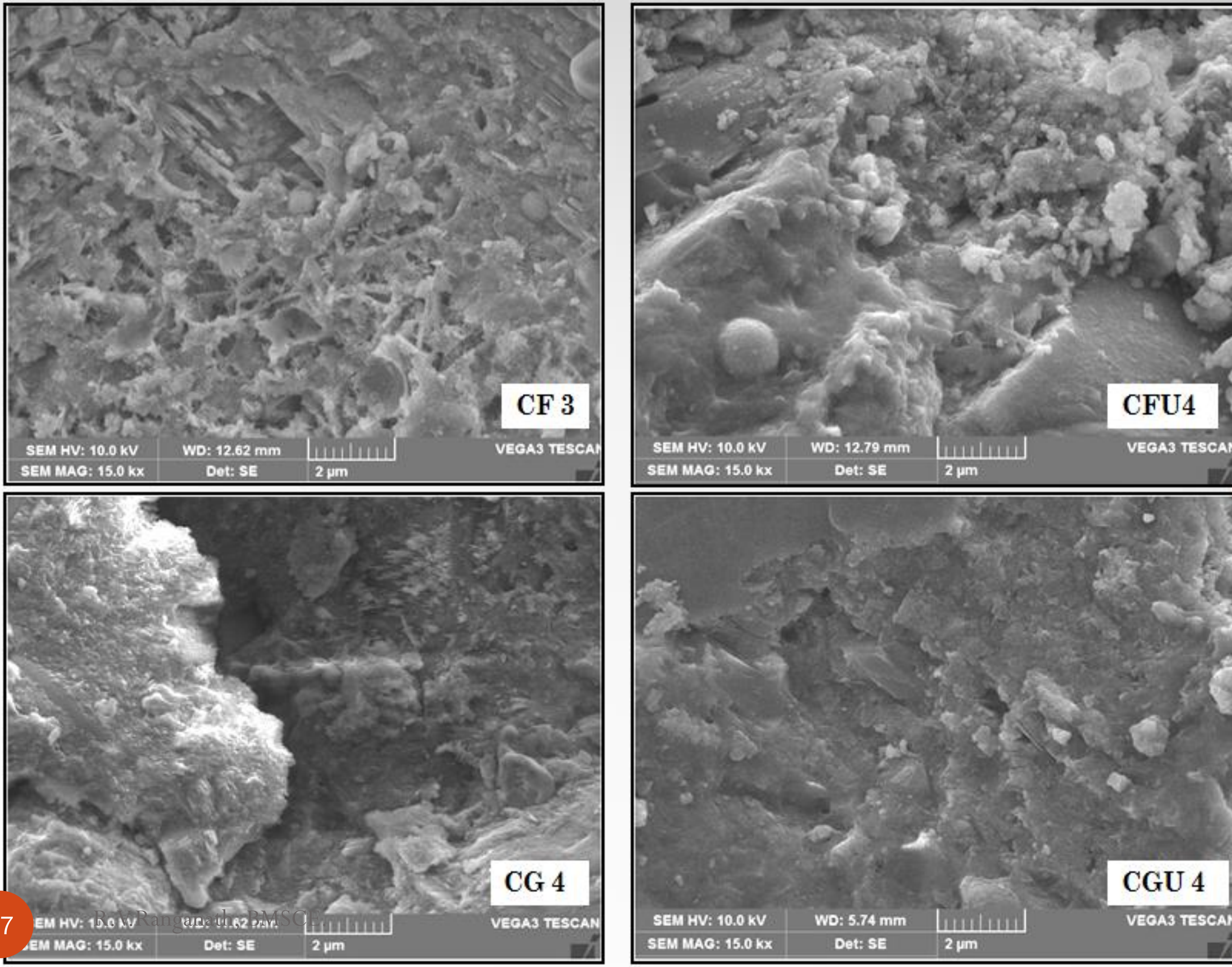
Concrete performance Evaluation

MICROSTRUCTURAL PROPERTY:

- The microstructural phases is observed to be more dense with continuous CSH formation in comparison with control for subsequent stages of mineral admixture blending.



SEM image of Control mix -CC


CF 3
SEM HV: 10.0 kV
WD: 12.62 mm
VEGA3 TESCAN
SEM MAG: 15.0 kx
Det: SE
2 μm
CFU4
SEM HV: 10.0 kV
WD: 12.79 mm
VEGA3 TESCAN
SEM MAG: 15.0 kx
Det: SE
2 μm
CG 4
VEGA3 TESCAN
Det: SE
2 μm
CGU 4
SEM HV: 10.0 kV
WD: 5.74 mm
VEGA3 TESCAN
SEM MAG: 15.0 kx
Det: SE
2 μm

B. High Early strength HSC

- Performance of High early strength is targeted with addition of ultra fine additives such as Ultra fine silica (nano silica) , Graphene oxide and Multi walled CNT under quaternary blending.
- Nano additives are added in separate sets for certain optimized mixes from ternary blend concrete mixes with OPC, GGBS, and Ultra fine Slag as Cementitious components
- Water and chemical admixtures is maintained constant for mixes.

Case study for Ultra fine Silica (UFSi) addition

Mix Series	Mix ID	Paste Volume	OPC kg/m³	FA kg/m³	Water kg/m³	%SP	Aggregate Volume	UFMAs, by % wt of OPC		Flow mm
								UFS	UFSi	
1: Binary blend	C1	0.32	450	90	135	0.5	0.68	-	-	520
	C2	0.34	450	126	135	0.5	0.66	-	-	540
	C3	0.36	450	168	135	0.5	0.64	-	-	560
	C4	0.38	450	210	135	0.5	0.62	-	-	580
	C5	0.4	450	252	135	0.5	0.6	-	-	530
Reference from Series 1							**Mix C4**			
2:Ternary blend	CA-1	0.38	450	210	135	0.5	0.62	2	-	580
	CA-2	0.39	450	210	135	0.5	0.61	4	-	570
	CA-3	0.39	450	210	135	0.5	0.61	6	-	550
	CA-4	0.39	450	210	135	0.5	0.61	8	-	530
	CA-5	0.39	450	210	135	0.5	0.61	10	-	490
Reference from Series 2							**Mix CA-4**			
3A: Quaternary blend : Water suspended UFSi	CSD-1	0.39	450	210	135	0.5	0.61	8	0.25	530
	CSD-2	0.39	450	210	135	0.5	0.61	8	0.5	530
	CSD-3	0.39	450	210	135	0.5	0.61	8	1	520
	CSD-4	0.39	450	210	135	0.5	0.61	8	1.5	490
3B: Quaternary blend : Direct Powder UFSi	CSP-1	0.39	450	210	135	0.5	0.61	8	0.25	540
	CSP-2	0.39	450	210	135	0.5	0.61	8	0.5	530
	CSP-3	0.39	450	210	135	0.5	0.61	8	1	530
	CSP-4	0.39	450	210	135	0.5	0.61	8	1.5	510

Addition of UFSi in the range of 0.25 to 1.5%wt of OPC in aqueous dispersion as well as direct powder state

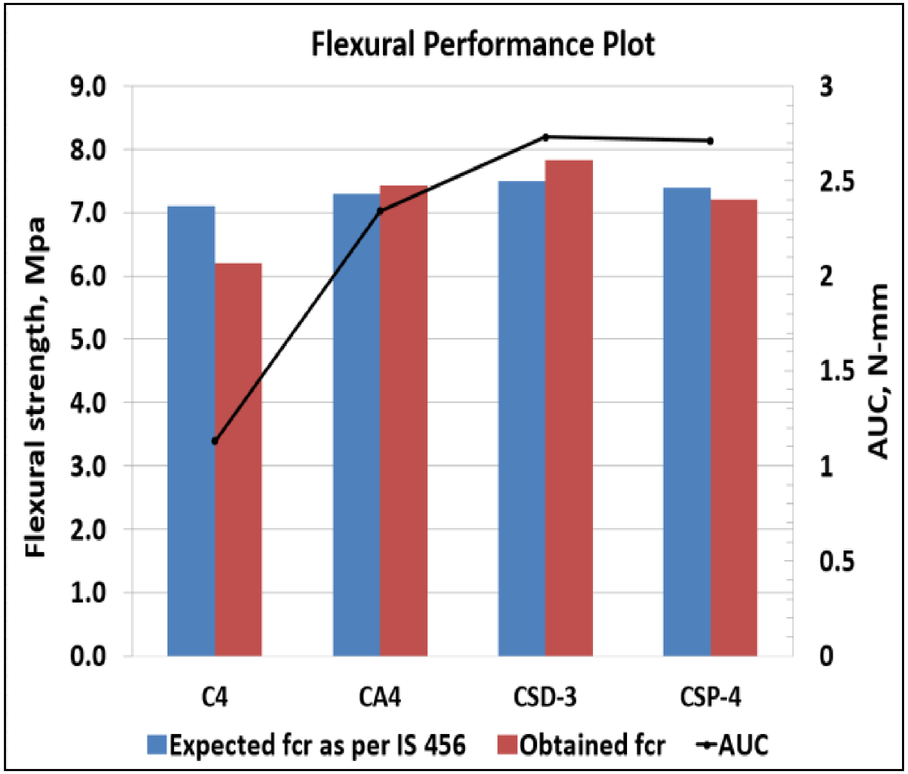
Observed results for strength and performance

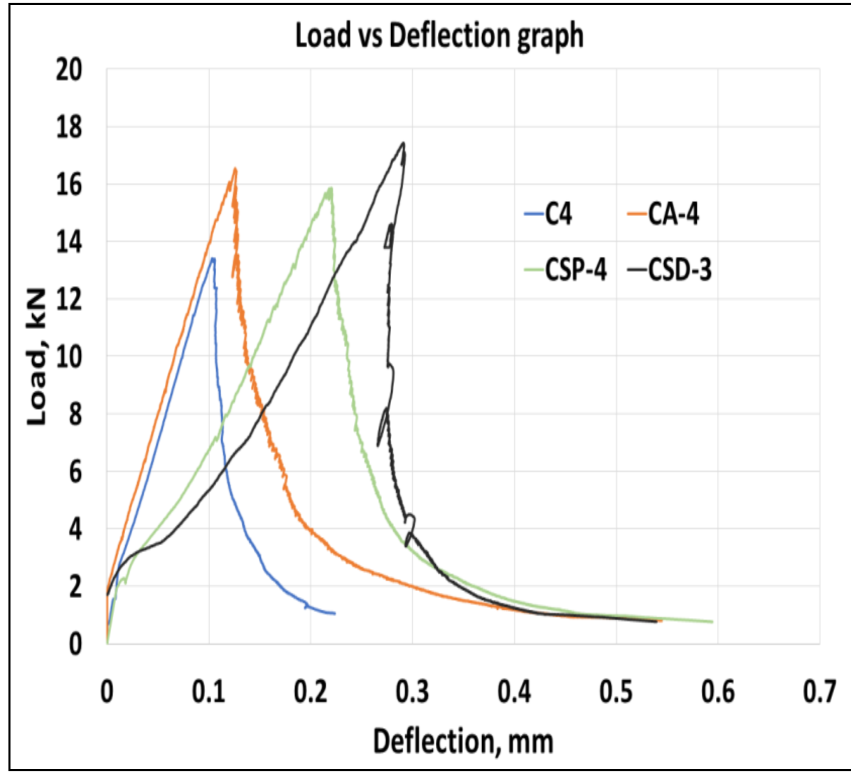
Mix Series	Mix ID	Compressive Strength, MPa at different time period					
		14 hours	24 hours	3 days	7 days	28 days	56days
Series1	C-1	15	28	65	78	93	95
	C-2	13	28	68	82	95	98
	C-3	14	27	61	81	98	105
	C-4	**14**	**25**	**65**	**85**	**104**	**110**
	C-5	11	20	58	76	99	110
Series2	CA-1	16	33	67	84	103	110
	CA-2	16	34	70	85	104	115
	CA-3	18	36	73	87	106	116
	CA-4	**22**	**36**	**72**	**86**	**110**	**121**
	CA-5	18	36	74	83	103	114
Series3- A	CSD-1	26	43	76	85	106	121
	CSD-2	31	46	79	88	109	122
	CSD-3	**31**	**49**	**85**	**95**	**114**	**127**
	CSD-4	29	44	82	87	112	124
Series 3-B	CSP-1	23	43	82	92	110	120
	CSP-2	30	47	84	94	108	124
	CSP-3	30	51	85	95	107	122
	CSP-4	**32**	**51**	**87**	**96**	**112**	**126**

- Compressive strength as high as 32 MPa in 14hours of casting and 51 MPa by 24 hours
- Ultimate strength greater than 120MPa is recorded after 56 days of curing with addition of Ultra fine Silica.

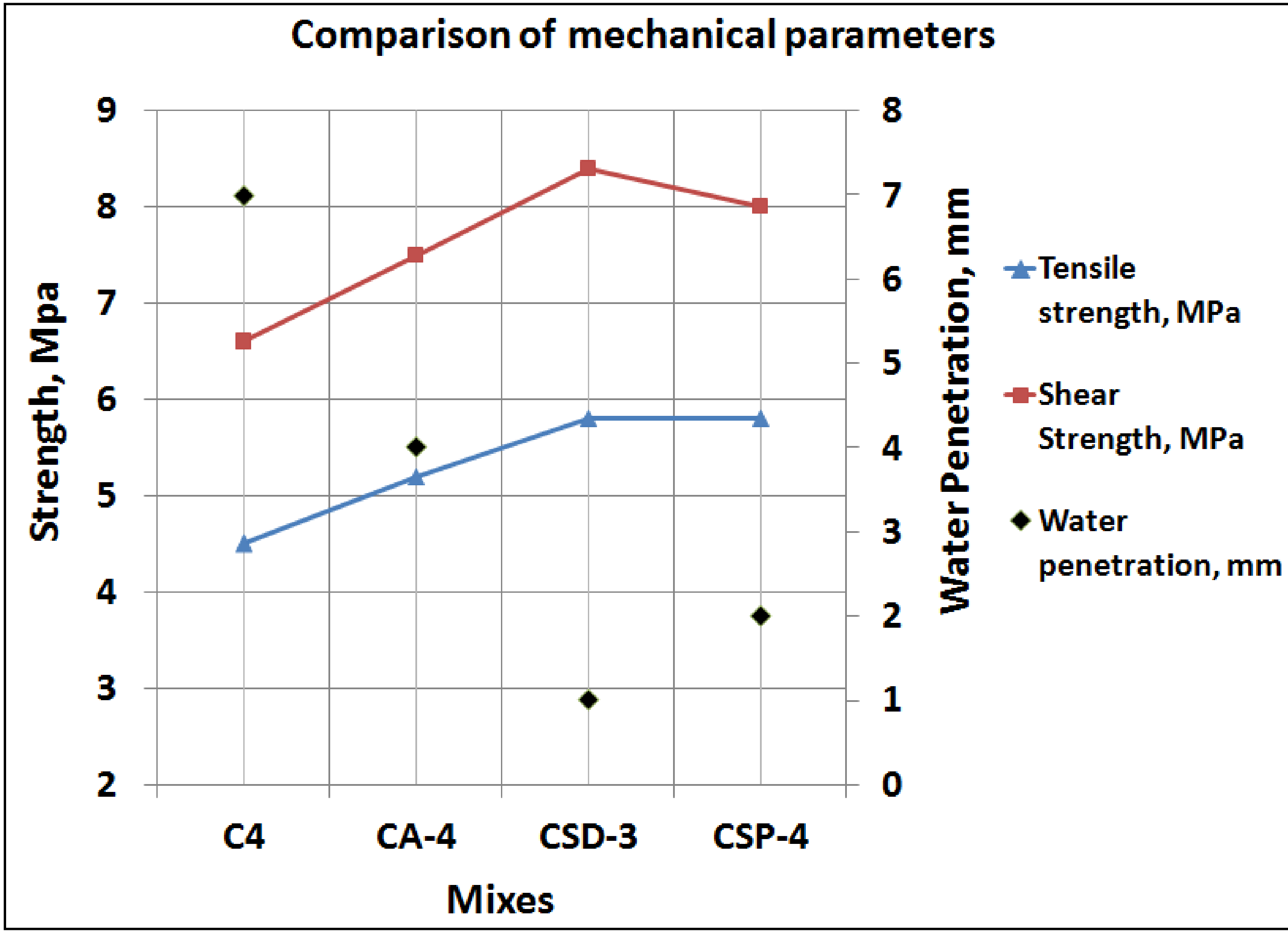
*Shamanth Gowda.T and R. V. Ranganath, Materials Today: Proceedings, March 2020

Flexural performance





- Improvement in flexural strength in comparison to control for blended HSC with Ultra fine mineral admixtures
- Greater Flexural toughness parameters with addition of Ultra fine admixtures in terms of Area under load- deflection curve



- Enhanced tensile and shear strength.
- Greatly reduced water permeability.

Non-Pozzolanic Ultra fine (Carbon) addition

- *Graphene Oxide (GO)* and *MWCNT* are two identified variants of UFC added in separate batches to ternary optimized mixes with OPC, GGBS and UFS

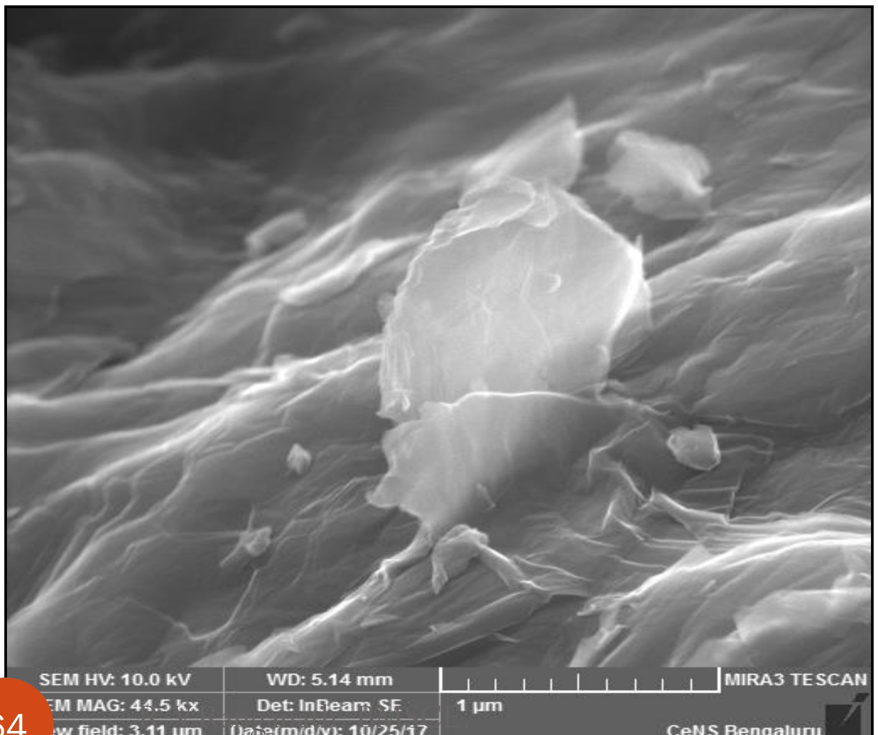
- One optimized mix from ternary blend selected for quaternary blend with Ultra fine additives:
  - Graphene oxide added at minute dosages from 0.025 to 0.15 % weight of Cement in separate mixes.
  - Multi walled CNT added at a fixed dosage of 0.05%wt of cement.
  - Aqueous dispersion of Carbon base ultra fine additives by ***sonication*** process is practiced.

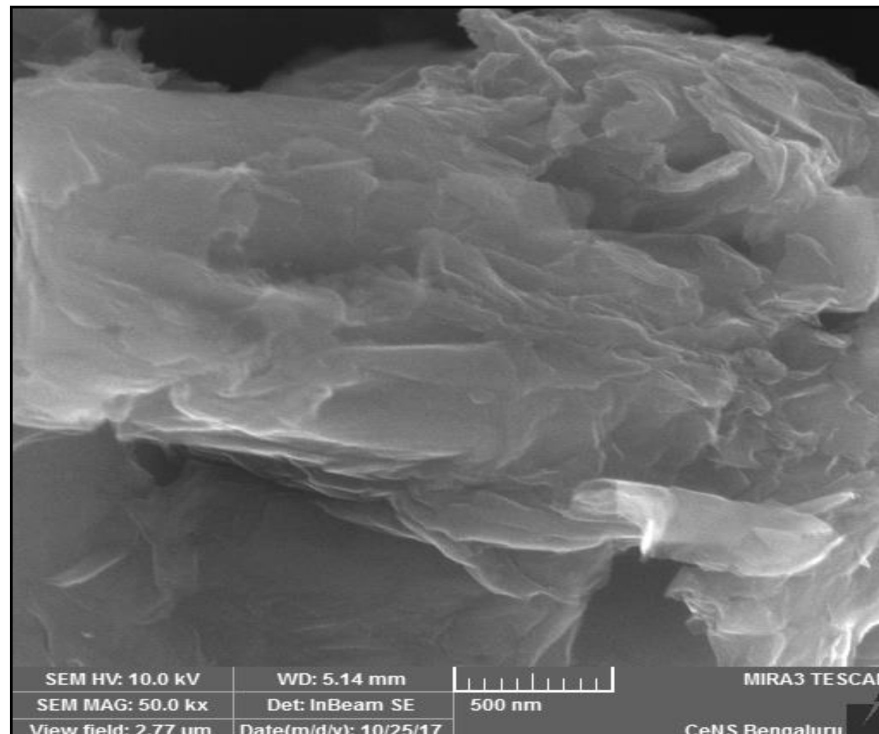
- When water is kept constant and dosage of super plasticizer is also unaltered, Addition of Ultra fine Carbons even at a minute dosage reduces the workability of concrete, owing to their greater specific surface area and morphology.

GRAPHENE OXIDE

Parameters	Approx. Value
Thickness	0.8 to 2nm
Lateral dimension	5-10 μm
Surface area	> 120 m^2/g
Carbon Purity	~99%
Specific gravity	1.009

(SOURCE : United Nano Tech Innovations Private Limited)

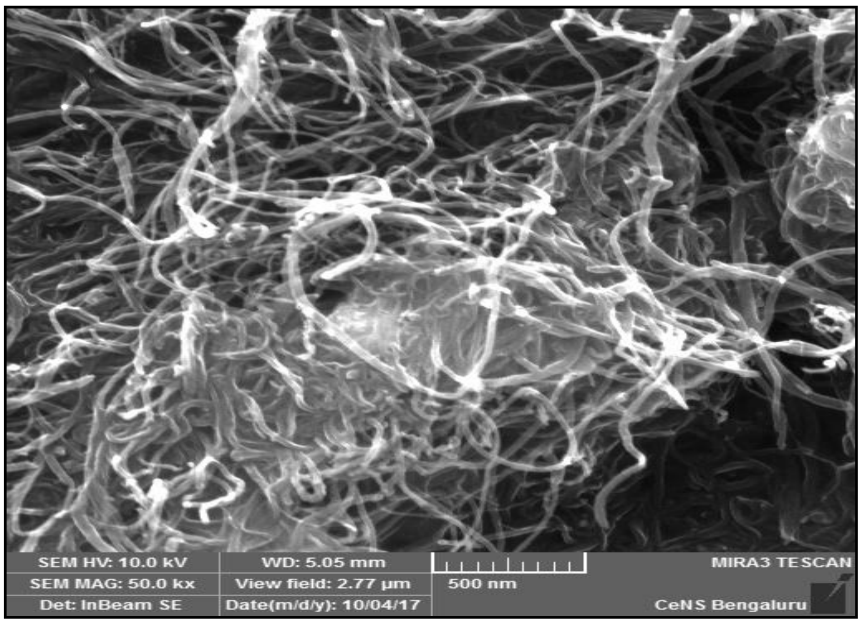


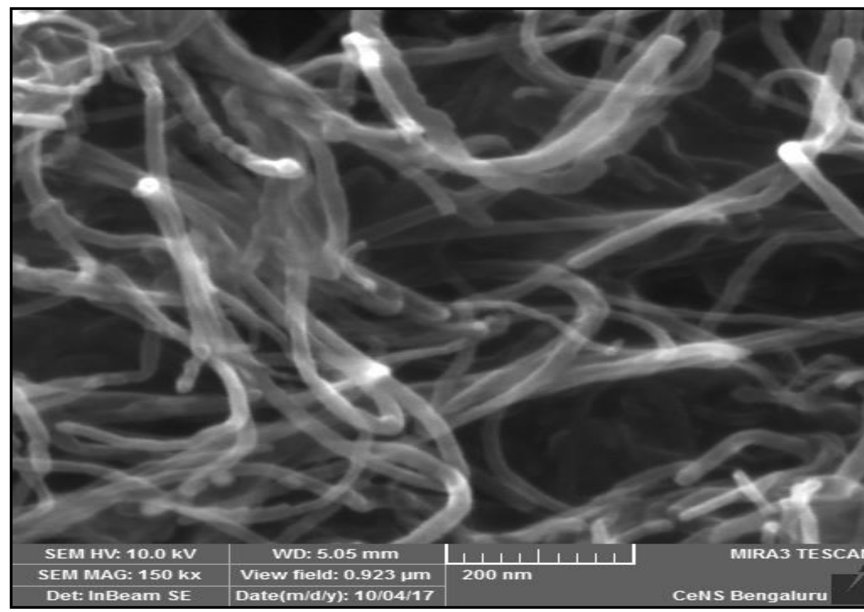


MULTI WALL CARBON NANO TUBE (MWCNT)

MWCNT Parameters	Approx. Value
Diameter	10-30 nm
Length	10 micron
Surface area	330 m^2/g
Carbon Purity	> 95%
Specific gravity	1.007

(SOURCE : United Nano Tech Innovations Private Limited)





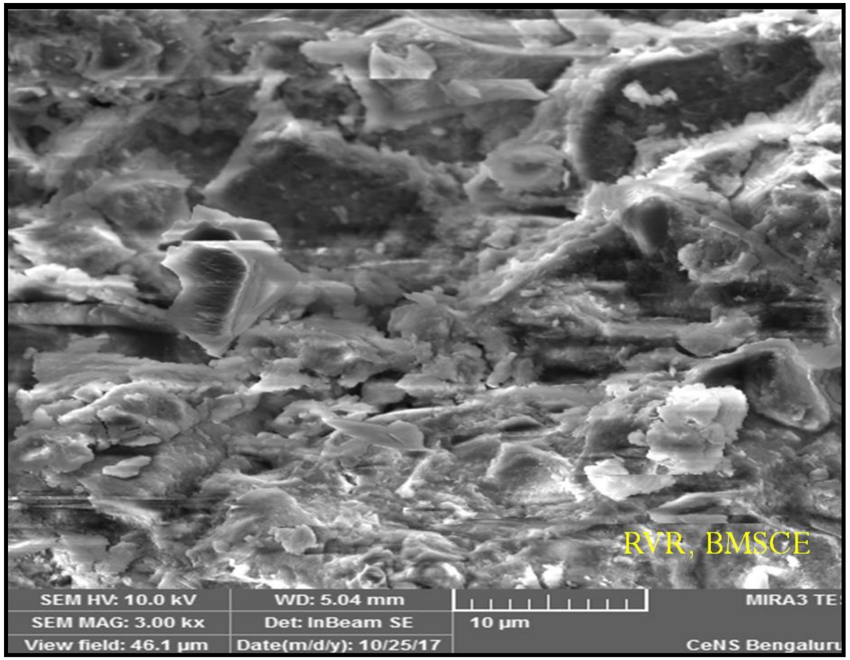
Compressive strength result of selected optimum mixes.

Mix Designation	3 DAYS	7 DAYS	28 DAYS
CONTROL (only OPC and GGBS)	60.0	89.4	110.8
GO-4 (at 0.15%wt)	72.5	104.9	127.8
CNT- 1 (at 0.05%wt)	94.7	103.8	110.0

* Research work, BMSCE.

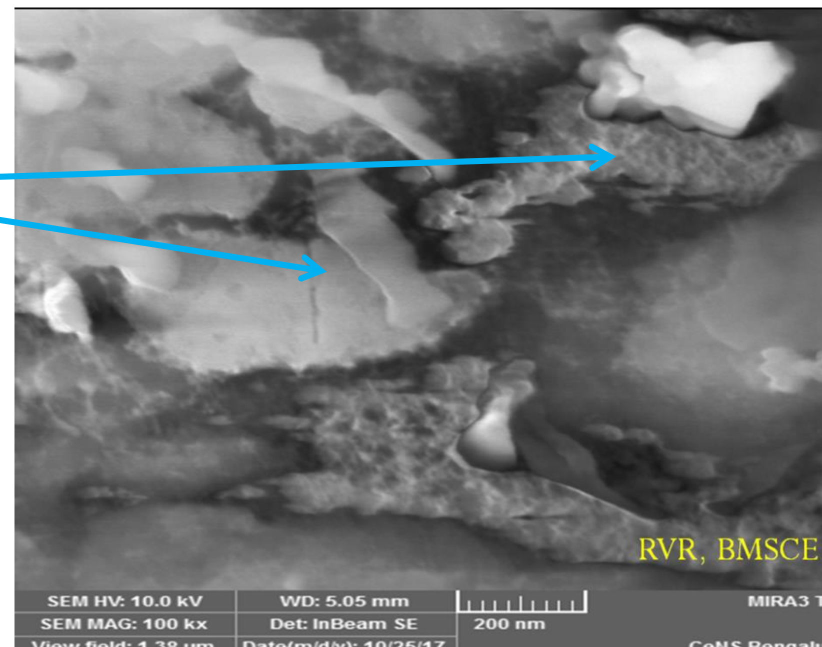
With CNT addition, even at 0.05%wt of OPC, very high early strength is evident, 94MPa after 3 days of casting.

For GO addition even with comparatively higher early strength, the Ultimate strength has greatly improved with 127MPa strength at 28th day of curing.
Nano pore filling and creation of more nucleation sites by GO's greater surface area could be the reason for such later day strength development

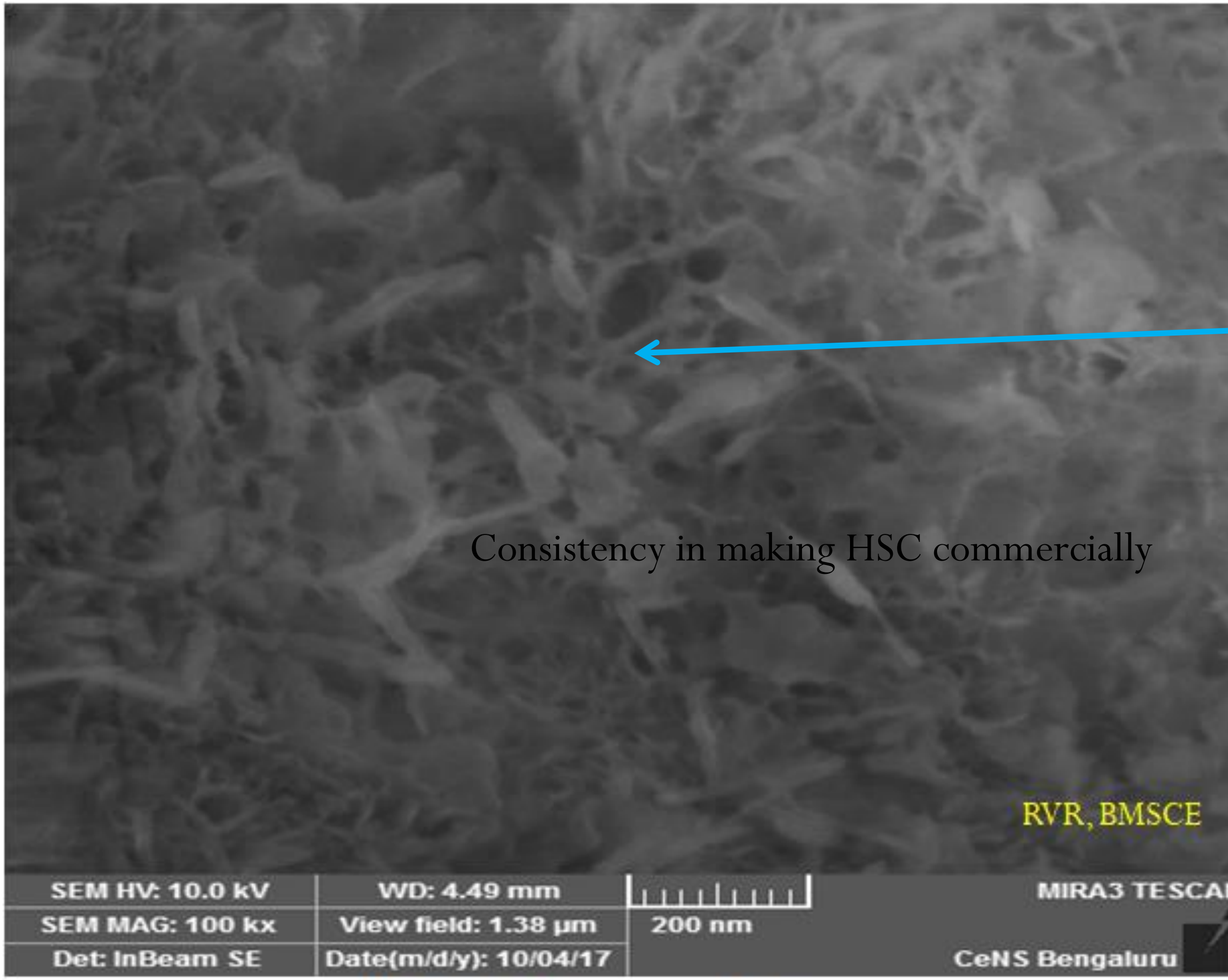


SEM image of GO-4 at 3kx

GO flakes and CSH at ITZ



SEM image of GO-4 at 100kx



SEM of CNT mix at 100kx

Consistency in making HSC commercially

CNT embedded in CSH phases

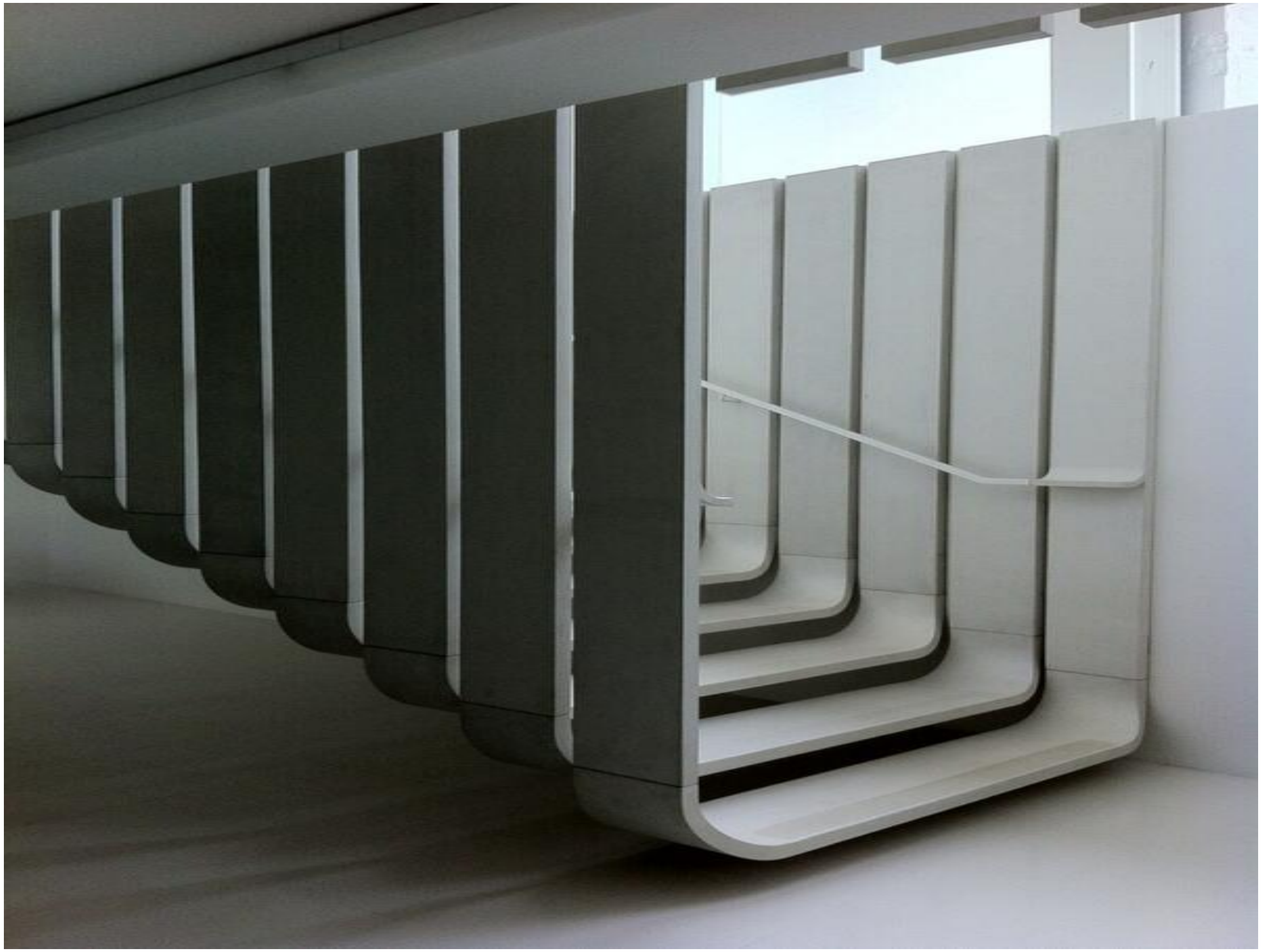
Few prominent structures realized by HSC/ HPC

High rise buildings

Bridges.

Road infrastructure.

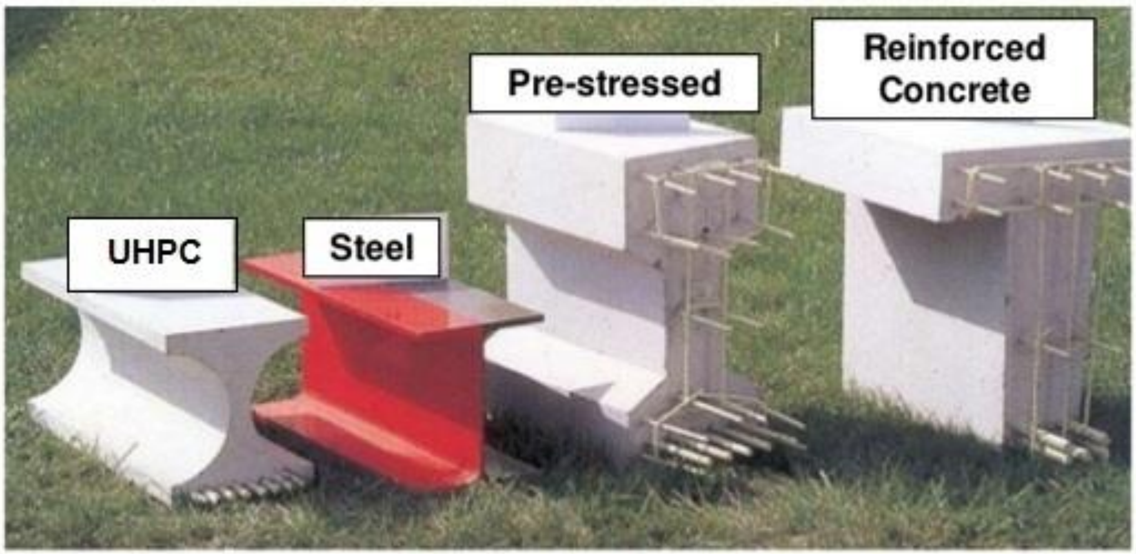
Architectural Precast units



Precast structural sections

Ultra-High Strength

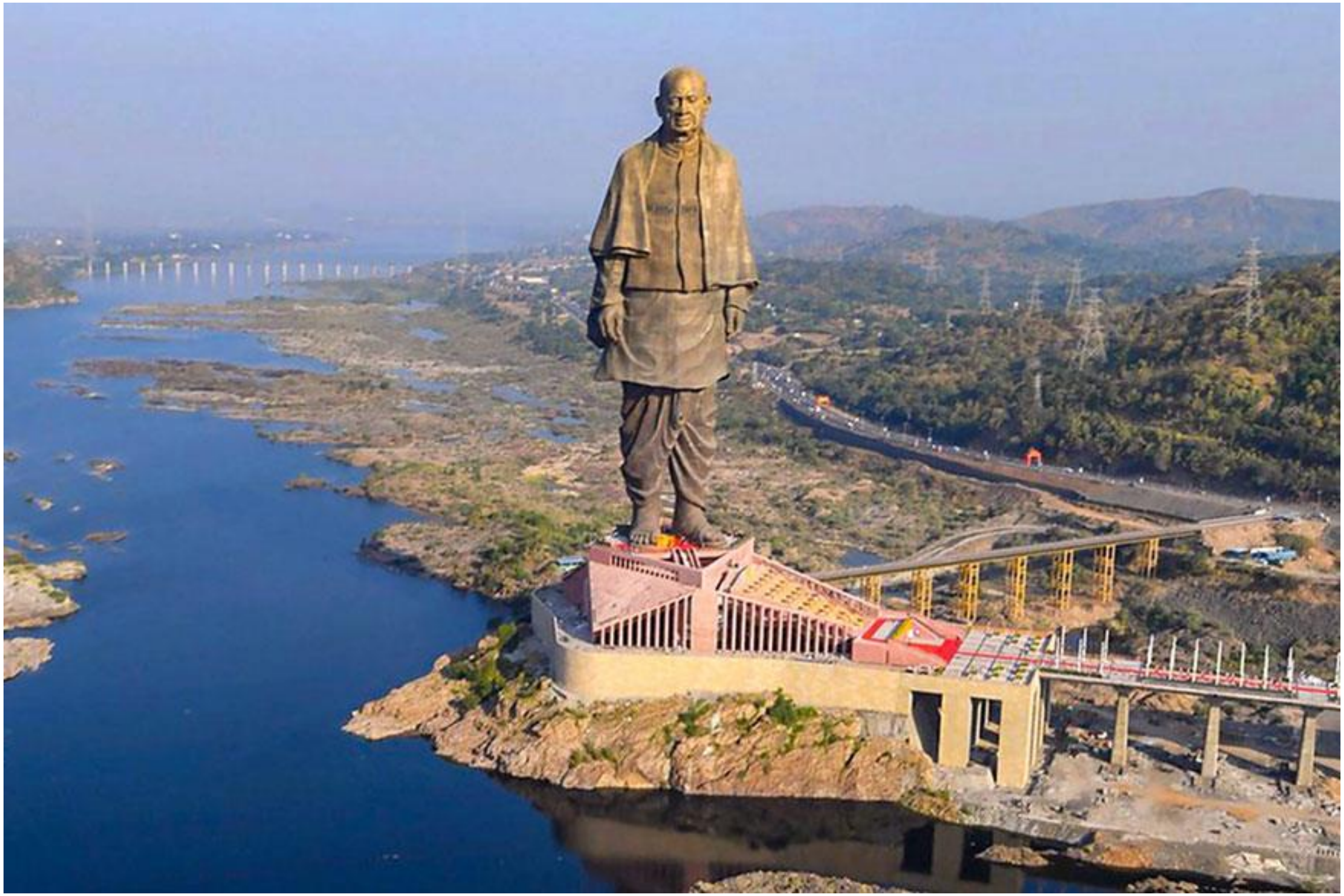
Beams of Equal Load Carrying Capacity



Mass (weight) of Beams

	UHPC	Steel	Pre-stressed	Reinforced Concrete
kg/lineal meter	140	112	467	530
lbs/lineal ft.	94	75	313	355

Monuments



What are the Road Blocks?

- Availability of Raw materials
- Consistency in making HSC commercially
- Performance evaluation standards
- Cost of Production.
- Reluctance of Designers
- Demand for High rise buildings in Urban landscape.

Concluding Remarks

- High strength is an achievable task in modern days due to advancement in material science.
- But, Performance of HSC is a subjective criteria.
  - *The designer can decide what performance he or she wants and plan accordingly.*
- Any mix related performance of HSC should be studied for *repeatability* before actual implementation.
- *Compatibility* of different admixtures used in HSC , both mineral and chemical, shall be verified for long term strength and durability behavior.
- There will be greater demand for such material in future due to increased demand for higher strength to weight of structures/space optimization.

Thank you…

Happy to Answer any Questions………