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# Effect of Particle Packing Optimization on the Mechanical Properties of Ultra High-Performance Concrete Incorporating Nano Silica

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*Abstract* – **The study focuses on the effect of particle packing optimization on the mechanical properties of Ultra High Performance Concrete (UHPC) incorporating nano silica. To achieve maximum packing density, the Modified Andreasen and Andersen particle packing model using EMMA software was adopted. The materials used in this study include cement, silica fume, quartz powder, fine sand, and nano silica. A very low water–binder ratio of 0.20 was adopted, and to balance the water requirement, a PCE-based Viscosity modifying admixture, Auramix 700HS, was used. Hand mixing was adopted for material preparation, and specimens were cast in cylindrical moulds. Flow table tests were conducted to evaluate flow parameters, followed by compressive strength and split tensile strength tests under a very low loading rate of 0.001 mm/sec (displacement-controlled loading). The results indicate that nano silica improves the behavior of concrete. The study demonstrates that proper particle packing combined with nano silica incorporation helps achieve Ultra High Performance Concrete with enhanced strength and durability. This work provides a foundation for future research and development of UHPC for structural applications by manual mixig.**

*Keywords* - **Ultra High Performance Concrete (UHPC), Particle Packing, Nano Silica, EMMA Software, PCE-based Viscosity modifying admixture, Compressive Strength, Split Tensile Strength.**

## 1. INTRODUCTION

Concrete is the most commonly and widely used construction material due to availability and cost effectiveness. But concrete has some limitations such as low tensile strength. Durability is reduced under some extreme environmental conditions, so to overcome these limitations advanced concrete like “Ultra High Performance- Concrete (UHPC)” has been developed. Ultra High-Performance Concrete is a special type of concrete which has very high compressive strength, lower porosity, and high durability.

The UHPC is developed by completely eliminating the coarse aggregate and using only fine materials such as silica fume, quartz powder, nano silica and fine sand. The elimination of coarse aggregate will reduce the weak zones in the concrete and improve the bonding between the particles.

Due to this highly dense particle packing, the mechanical properties of concrete are improved. Particle packing is one of the very important principles used in Design of UHPC.

## 2.PARTICLE PACKING USING EMMA SOFTWARE.

Particle packing concept is very important to prepare the mix design of UHPC. Particle packing concept helps us to know which mix gives us the maximum packing. Modified Andreasen Equation is used to obtain dense packing of materials.

***Modified Andreassen Equation***

$$P(D) = \frac{D^q - D^q_{\min}}{D^q_{\max} - D^q_{\min}}$$

Where:

- $P(D)$ = fraction (or % passing) of particles smaller than size $D$
- $D$ = particle size
- $D_{\min}$ = minimum particle size
- $D_{\max}$ = maximum particle size
- $q$ = distribution modulus (key parameter)

***Materials:***

- Fine Sand [600 µm]
- Ordinary Portland cement 53 Grade [ 75 µm]
- Quartz powder [75 µm]
- Silica fume [ 13 µm]
- Nano Silica [0.02 µm]
- PCE-based Viscosity modifying admixture (2% of binder)
- Water (W/b = 0.20)

EMMA software (Fig.1) adopts the Modified Andreasen equation and uses particle size distribution values to generate particle packing curves. Particle packing curves for the mixes is given in Fig 2-6.

***EMMA Model Settings:***

Distribution model: modified Andreassen
q = 0.23
Dmax = 600 µm
Dmin = 0.1 (silica fume) (or) 0.02 µm (nano silica)

EMMA Mix Analyzer
Program build version 3.5.2.11
Please wait while the program initializes..

Fig.1 EMMA Mix Analyze

### 2.1. *Particle Packing Curves:*

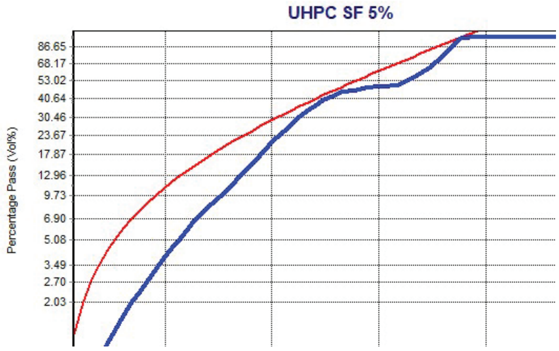


Fig.2 Particle Packing Curve UHPC SF 5%

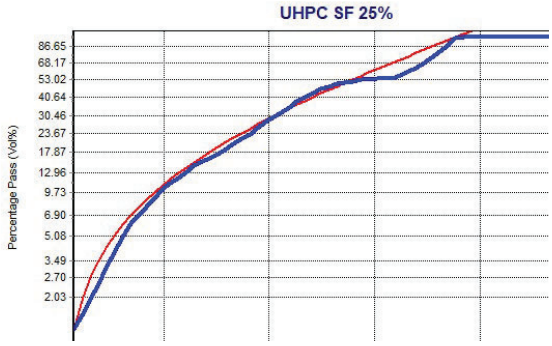


Fig.3 Particle Packing Curve UHPC SF 25%

Table.1 UHPC SF 5%

| Mix ID | Cement | Silica Fume | Quartz Powder | Fine Sand | Nano Silica |
|---|---|---|---|---|---|
| UHPC SF 5% | 600 Kgs | 30 Kgs | 100 Kgs | 750 Kgs | 0 Kgs |

Table.2 UHPC SF 25%

| Mix ID | Cement | Silica Fume | Quartz Powder | Fine Sand | Nano Silica |
|---|---|---|---|---|---|
| UHPC SF 25% | 600 Kgs | 150 Kgs | 100 Kgs | 750 Kgs | 0 Kgs |

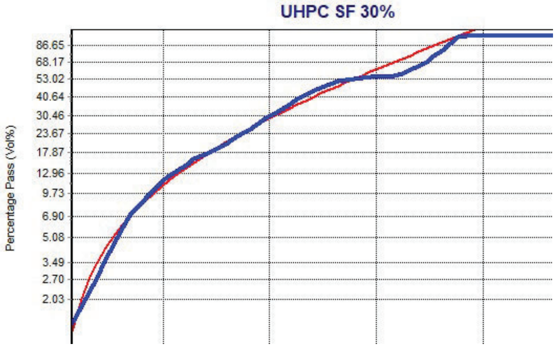


Fig.4 Particle Packing Curve UHPC SF 30%

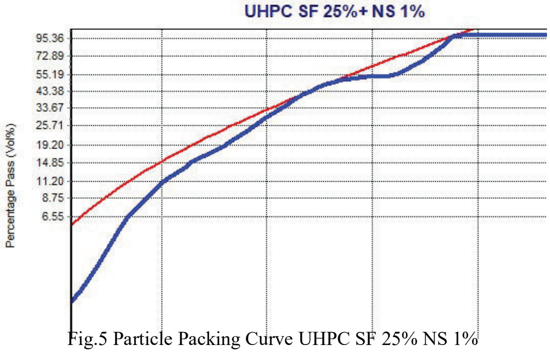


Fig.5 Particle Packing Curve UHPC SF 25% NS 1%

Table.3 UHPC SF 30%

| Mix ID | Cement | Silica Fume | Quartz Powder | Fine Sand | Nano Silica |
|---|---|---|---|---|---|
| UHPC SF 30% | 600 Kgs | 180 Kgs | 100 Kgs | 750 Kgs | 0 Kgs |

Table.4 UHPC SF 25% NS 1%

| Mix ID | Cement | Silica Fume | Quartz Powder | Fine Sand | Nano Silica |
|---|---|---|---|---|---|
| UHPC SF 25% + NS 1% | 600 Kgs | 150 Kgs | 100 Kgs | 750 Kgs | 7.5 Kgs |

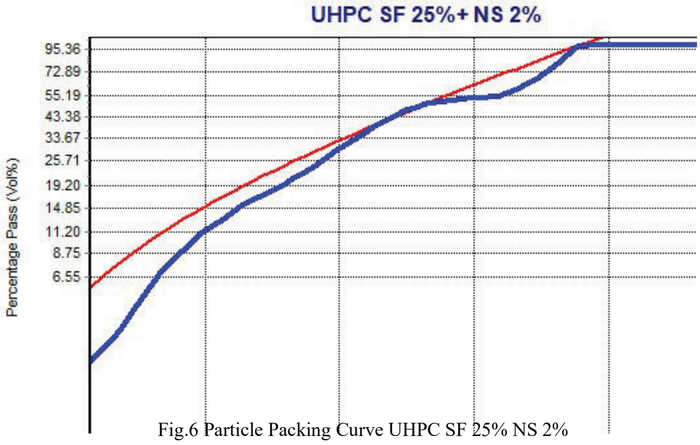


Fig.6 Particle Packing Curve UHPC SF 25% NS 2%

Table.5 UHPC SF 25% NS 2%

| Mix ID | Cement | Silica Fume | Quartz Powder | Fine Sand | Nano Silica |
|---|---|---|---|---|---|
| UHPC SF 25% + NS 2% | 600 Kgs | 150 Kgs | 100 Kgs | 750 Kgs | 15 Kgs |

## 3.PREPARATION OF UHPC:

Mixing was carried out manually in small batch quantities. However, mechanical mixing is generally recommended for Ultra High Performance Concrete (UHPC), as it requires adequate shear energy and continuous mixing for approximately 30–40 minutes to achieve proper homogeneity.

***The mixing procedure adopted in this study is as follows:***

- All dry materials were initially mixed for 5 minutes until a uniform colour was obtained.
- The admixture solution along with 70% of the required water was added within 1–2 minutes and mixed thoroughly.
- The mixture was continuously mixed for approximately 15 minutes until the colour changed to a dark black appearance. At this stage, the remaining 30% of water was added gradually.
- After the addition of the remaining water, the mix started exhibiting flow characteristics and mixing was continued to get a uniform mix.

Fig.7 Prepared Mould [Dia-72mm, Depth-144mm]

Fig.8,9 Casting & Curing of Specimens

Cylindrical specimens 72mm and 144mm are cast in a PVC pipe specially cut to the required dimensions Fig 7,8,9.

The specimens were demoulded after 24 hours and cured for 28 days.

## 4.RESULTS

***4.1. Flow Table Results:*** Consistency of the UHPC mix is determined using flow table Fig 10. The results are given in Table 6. The UHPC SF 30% and UHPC SF 25% have the maximum flow and these results reflect the optimum packing density as in Fig 3and 4. Thus, Optimum packing density can be achieved from Modified Anderson Method. In this case, the value of q= 0.23 is the best one.

Table.6 Flow Table Results

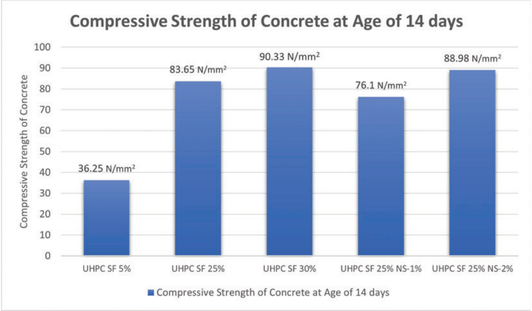
| Mix ID | Flow Length ($D_{avg}$) | Flow % |
|---|---|---|
| UHPC SF 5% | 14.4cm | 80% |
| UHPC SF 25% | 17.5cm | 118.75% |
| UHPC SF 30% | 18.2cm | 127.5% |
| UHPC SF 25% + NS 1% | 16.8cm | 110% |
| UHPC SF 25% + NS 2% | 16.2cm | 102.5% |

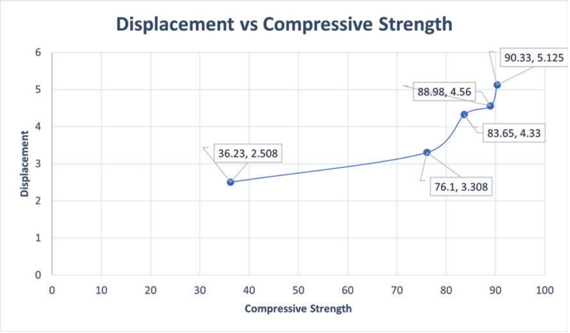
Fig.10 Flow Table Test

***4.2. Compressive Strength Test:*** The specimens are tested for compressive strength and split tensile strength in a UTM under displacement control at the rate of 0.001mm/sec. The tested specimens are shown in Fig 12. The results are given in Tables 7 and 8, the plot is shown in Fig below and 11 for compressive strength and split tensile strength respectively. Compressive strength for UHPC SF 30% is the highest and conspicuously split tensile strength is low. UHPC SF25% + NS 2% also gave almost the same results as UHPC SF 30%. A comparison shows that the Modified Anderson method is useful in proportioning the ingredients of UHPC to achieve an optimum mix.

Table.7 Compression Strength Test After 14days

| Mix ID | Load (KN) | Displacement (mm) | Area ($mm^2$) | Stress or Compressive Strength ($N/mm^2$) |
|---|---|---|---|---|
| UHPC SF 5% | 147.5 | 2.51 | 4071.50 | 36.23 |
| UHPC SF 25% | 340.6 | 4.33 | 4071.50 | 83.65 |
| UHPC SF 30% | 367.6 | 5.13 | 4071.50 | 90.33 |
| UHPC SF 25% + NS 1% | 309.8 | 3.31 | 4071.50 | 76.10 |
| UHPC SF 25% + NS 2% | 362.3 | 4.56 | 4071.50 | 88.98 |





### *3. Split Tensile Strength Test:*

Table.8 Split Tensile Strength Test Results After 14days

| **Mix ID** | **Load [P] (KN)** | **Diameter [d] (mm)** | **Length [L] (mm)** | **Split Tensile Strength $\left(\frac{2P}{\pi d L}\right)$ (N/mm$^2$)** |
|---|---|---|---|---|
| UHPC SF 5% | 60.6 | 72 | 144 | 3.72 |
| UHPC SF 25% | 77.8 | 72 | 144 | 4.70 |
| UHPC SF 30% | 49.9 | 72 | 144 | 3.06 |
| UHPC SF 25% + NS 1% | 100.2 | 72 | 144 | 6.15 |
| UHPC SF 25% + NS 2% | 110.6 | 72 | 144 | 6.79 |

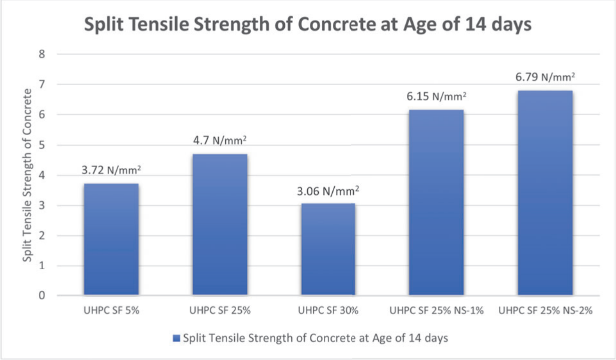


Fig.11 Crack Formed in the Specimen

Fig.12 Broken Specimen

## CONCLUSION

The study demonstrates that the performance of Ultra High Performance Concrete (UHPC) is strongly influenced by Particle Packing optimization and incorporation of Nano silica. Different mix variations were analyzed by varying silica fume and nano silica content, and their effects on flow parameters, compressive strength, and split tensile strength were evaluated.

The study observed that variation in silica fume content from 5% to 30% resulted in improved workability and strength. As observed from the experimental results, increase in silica fume content improved the flow characteristics as the silica fume helps to fill the micro-level voids and improve packing. The compressive strength increased from 36.23 MPa (SF 5%) to 90.33 MPa (SF30%), indicating that higher silica fume content contributes denser and stronger concrete.

The incorporation of nano silica (1% to 2%) further influenced the mechanical properties. From the compressive strength results, the strength increased to 88.98 MPa for 2% Nano Silica compared to 83.65 MPa for the base mix of 25% Silica Fume mix. Similarly, split tensile strength improved from 4.70 MPa to 6.79 MPa. This improvement is due to nano filling effect and accelerated hydration process.

The relationship between flow parameters and strength indicates that good workability is required for proper compaction and reduction of air voids. Mixes with high flow values observed better compaction and strength, whereas reduced flow in nano silica mixes required careful water and admixture adjustment.

Overall, the results confirm that UHPC performance depends on a combined effect of particle packing density, material fineness, and mix workability rather than a single parameter. Optimized particle packing with controlled addition of silica fume and nano silica produces a dense microstructure, leading to enhanced compressive and tensile strength.

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