APPENDIX 1

MIX DESIGN PROCEDURE FOR HSC

A1.1 CONCEPTS OF MIX DESIGN FOR HSC

The main difference between mix design of HSC and CCC is the emphasis laid on strength and performance aspect. In HSC, besides strength and durability, considerations are given to behaviour of concrete in the fresh state. From the general principles behind the design of HSC mixtures, it is apparent that high strengths are made possible by reducing porosity, non-homogeneity, and micro cracks in the hydrated cement paste and the transition zone. To achieve high strength, durable and workable high strength concrete, the mix design of HSC should be based on the following considerations:

- In HSC, the aggregate plays an important role on the strength of concrete

- The low-water to cement ratio, preferably 0.3 and below, used in high-strength concrete causes densification in both the matrix and interfacial transition zone, and the aggregate may become the weak link in the development of the mechanical strength.

- Extreme care is necessary in the selection of aggregate to be used in very high-strength concrete. The particle size distribution of fine aggregate that meets the ASTM specifications is adequate for high-strength concrete mixtures.
If possible, Aitcin (1998) recommended using fine aggregates with higher fineness modulus (around 3.0). Hence, use of coarser sand conforming to zone I / II of BIS: 383-1970 (36) is required for achieving higher strength and increasing the workability of concrete.

- The maximum size of coarse aggregate should be restricted to 12.5mm, as smaller size aggregates are required for achieving higher strength.

- The workability of the concrete should be good enough to obtain good compaction by adding suitable chemical admixtures, such as superplasticizer.

- The transition zone between aggregates and cement paste should be strengthened by partial replacement of cement with mineral admixtures (micro fillers), such as silica fume, fly ash etc., also such a partial replacement of cement with pozzolanic admixtures improve the micro structure of cement so that the concrete becomes dense and impermeable.

- Proper curing of concrete should be ensured.

A1.2 METHOD OF MIX DESIGN

The mix design procedure for NSC as presently prevailing in India, is not found suitable for mix design of HSC using mineral admixtures. The American Concrete Institute (ACI) methods are available for both NSC and HSC. The ACI method of mix design for HSC considers only the use of fly ash and superplasticizers. Since there is no specific method of mix design found suitable for HSC, a simplified mix design procedure is formulated by combining the BIS method, ACI method and the available published literatures on HSC, using fly ash and silica fume. It follows the same
approach as ACI method. It is a combination of empirical results and mathematical calculations based on the absolute volume method.

**A1.2.1 Mix design procedure for HSC**

To design a HSC mix using mineral admixtures, the following procedure is formulated:

**Step 1: Target mean-strength determination**

The target mean-strength ($f_{ck}$) is calculated as follows:

$$ (f_{ck}) = f'_{ck} + (t \times s) $$

Where

- $(f_{ck})$ = target mean-compressive strength at 28 days
- $(f'_{ck})$ = specified characteristics compressive strength at 28 days
- $t$ = statistical value depending on the accepted proportion of low results and the number of tests. As per the definition of characteristics strength in BIS: 456-2000, value of $t = 1.65$
- $s$ = standard deviation, depending on the grade of concrete and degree of control,

The value of ‘s’ is obtained from Table 1 of BIS: 10262-2009 (41).

When adequate data are not available to establish a standard deviation, the required or target mean - compressive strength can be determined from Table A1.1 as given by ACI report 318 (3):
Table A1.1 Target mean – compressive strength when data are not available to establish a standard deviation

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Specified characteristic compressive strength, $f'_{ck}$ (MPa)</th>
<th>Target mean – compressive strength, $f_{ck}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Less than 20.5</td>
<td>$f'_{ck}$ +6.9</td>
</tr>
<tr>
<td>2</td>
<td>20.5 - 34.5</td>
<td>$f'_{ck}$ + 8.3</td>
</tr>
<tr>
<td>3</td>
<td>More than 34.5</td>
<td>$f'_{ck}$ + 9.7</td>
</tr>
</tbody>
</table>

Step 2: Selection of maximum size of coarse aggregate

The maximum size of coarse aggregate is selected from Table A1.2 as given by ACI Report 211.4R.93 (1):

Table A1.2 Selection of maximum size of coarse aggregate

<table>
<thead>
<tr>
<th>Required concrete strength (MPa)</th>
<th>Maximum aggregate size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 62</td>
<td>20-25</td>
</tr>
<tr>
<td>Greater than or equal to 62</td>
<td>10 -12.5</td>
</tr>
</tbody>
</table>

Step 3: Estimation of free water content

The water content to be obtained for the desired workability/slump depends on the amount of water and amount of superplasticizer and its characteristics. However, if the saturation point of the superplasticizer is known, then the water dosage is obtained as suggested by Aitcin (1998). If the saturation point of the superplasticizer is not known, it is suggested that a water content of 145litres/m$^3$ shall be taken, to start with.
Step 4:  Superplasticizer dosage

The superplasticizer dosage is obtained from the dosage at the saturation point. If the saturation point is not known, it is suggested that a trial dosage of 1.0 percent shall be taken, to start with.

Step 5:  Estimation of air content

The air content (approximated amount of entrapped air) to be expected in HSC is obtained from Table A1.3 as given by ACI Report 211.4R.93 (1) for the maximum size of coarse aggregate used. However, it is suggested that an initial estimate of entrapped air content shall be taken as 1.5% or less, since it is HSC and then adjusting it on the basis of the result obtained with the trial mix.

Table A1.3 Approximate entrapped air content

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Nominal maximum size of coarse aggregate (mm)</th>
<th>Entrapped air, as per cent of volume of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>12.5</td>
<td>2.0</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Step 6:  Selection of coarse aggregate content

The coarse aggregate content is obtained from Table A1.4, as a function of the typical particle shape, as suggested by Aitcin (1998).
Table A1.4 Coarse aggregate content

<table>
<thead>
<tr>
<th>Coarse aggregate particle shape</th>
<th>Elongated/flat</th>
<th>Average</th>
<th>Cubic</th>
<th>Rounded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse aggregate Dosage kg/m³</td>
<td>950-1000</td>
<td>1000-1050</td>
<td>1050-1100</td>
<td>1100-1150</td>
</tr>
</tbody>
</table>

If there is any doubt about the shape of the coarse aggregate or if its shape is not known, it is suggested that a coarse aggregate content of 1000kg/m³ of concrete shall be taken, to start with. The coarse aggregate so selected should satisfy the requirements of grading and other requirements of BIS: 383-1970 (36).

**Step 7: Selection of w/b ratio**

The w/b ratio for the mean compressive strength is chosen from Figure A1.1 (proposed compressive strength vs w/b ratio relationship Aitcin (1998), pp.235, Figure 8.9).

![Figure A1.1 Proposed compressive strength vs w/b ratio relationship](image-url)
The w/b ratio so chosen is checked against the limiting w/b ratio for the requirements of durability as per Table 5 of BIS: 456-2000 (37) and the lower of the two values is adopted.

**Step 8: Calculation of binder contents**

The binder or cementitious contents per unit volume (m³) of concrete is calculated from the w/b ratio and the quantity of water content per unit volume of concrete. Assuming the percentage replacement of cement by silica fume and fly ash, the content of both cementitious materials are obtained from the total binder contents. The remaining binder content is composed of cement. The cement so calculated is checked against the minimum cement content for the requirements of durability as per Tables 5 and 6 of BIS: 456-2000 (37) and the greater of the two values are adopted.

**Step 9: Superplasticizer content**

The mass of solids in the superplasticizer (M_{sol}), the volume of liquid superplasticizer (V_{liq}), the volume of water in the liquid superplasticizer (V_w) and the volume of solids in the liquid superplasticizer (V_{sol}) are calculated from the following equations:

\[
M_{sol} = C \times d/100 \quad (2)
\]

\[
V_{liq} = (M_{sol} \times 100) / s \times S_s \quad (3)
\]

\[
V_w = V_{liq} \times S_s [(100-s) /100] \quad (4)
\]

\[
V_{sol} = V_{liq} - V_w \quad (5)
\]

Where

- \( M_{sol} \) = mass of solids (kg) in the superplasticizer
- \( V_{liq} \) = volume of liquid superplasticizer
\( V_w \) = volume of water in the liquid superplasticizer

\( V_{sol} \) = volume of solids in the liquid superplasticizer

\( C \) = mass of the cementitious materials (kg)

\( d \) = superplasticizer dosage expressed as the percentage of its solid content

\( s \) = total solid content of the superplasticizer in per cent, and

\( S_s \) = specific gravity of the liquid superplasticizer

**Step 10: Estimation of fine aggregate content**

The absolute volume of sand in litres per unit volume of concrete (m³) is obtained from the following equation:

\[
V_{fa} = 1000 - \left[ V_w + \frac{M_c}{S_c} + \frac{M_{sf}}{S_{sf}} + \frac{M_{ca}}{S_{ca}} + V_{sol} + V_{ea} \right]
\]  \( \cdots \) (6)

Where \( V_{fa} \) = absolute volume of sand in litres per unit volume of concrete (m³)

\( V_w \) = volume of water (litres) per unit volume of concrete (m³)

\( M_c \) = mass of cement (kg) per unit volume of concrete (m³),

\( S_c \) = specific gravity of cement

\( M_{sf}, M_{ca} \) = total masses of the silica fume (kg) and coarse aggregate (kg) per unit volume of concrete (m³), respectively

\( S_{sf}, S_{ca} \) = specific gravities of silica fume and saturated surface dry coarse aggregate, respectively, and
\( V_{\text{sol}}, V_{\text{ea}} = \) volume of solids in the superplasticizer and entrapped air (litres) per unit volume of concrete \((m^3)\), respectively.

The fine aggregate content per unit volume of concrete \((m^3)\) is obtained by multiplying the absolute volume of fine aggregate and the specific gravity of the fine aggregate.

**Step 11: Moisture adjustment**

The actual quantities of coarse aggregate, fine aggregate and water content are calculated, after allowing necessary corrections for water absorption and free (surface) moisture content of aggregates. The volume of water included in the liquid superplasticizer is calculated and subtracted from the initial mixing of water.

**Step 12: Unit mass of concrete**

The mass of concrete per unit volume is calculated by adding the masses of the concrete ingredients.

**Step 13: Trial mix proportion**

Using the mass of different ingredients for 1 \(m^3\) of concrete, the trial mix proportions by weight are arrived at.

**Step 14: Trial batch adjustments**

Because of many assumptions underlying the foregoing theoretical calculations, the trial mix proportions must be checked. If necessary, the mix proportion should be modified to meet the desired workability and strength criteria, by adjusting the percentage replacement of cement by silica fume, fly
ash, percentage dosage of superplasticizer solid content of binders, air content and unit weight by means of laboratory trail batches to optimize the mix proportion. Fresh concrete should be tested for workability. Specimens of hardened concrete should be tested at the specified age.

A1.3 MIX DESIGN FOR M40 GRADE CONCRETE

Step 1: Determination of Target- mean strength

Based on the Table A1.1 of ACI 318 (3), the target mean compressive strength $f_{ck}$ is as follows

$$f_{ck} = f_{ck}' + 9.7$$

$$=40 + 9.7 =49.7 \text{N/mm}^2$$

Step 2: Selection of maximum size of coarse aggregate

The coarse aggregate confirm to graded aggregate of nominal size 12.5mm as per table 2 of BIS 383-1970 (36) is adopted. Also based on Table A1.2 of ACI report 211.49.R3 (1), the size chosen is suitable for other grades viz M60 and M80.

Step 3: Determination of mixing water content

For M40 Grade concrete, the free water content chosen was 174 lits/m$^3$

Step 4: Determination of air-content

From Table A1.3 of ACI report 211.4R.93 (1), for nominal maximum size of coarse aggregate chosen (12.5mm), the approximate entrapped air content is 2%.
Step 5: Determination of coarse - aggregate content

As suggested by Aitcin(1998), coarse aggregate content as a function of typical particle shape, 1136 kg/m$^3$ has been selected for the M40 Grade concrete.

Step 6: Determination of w/c ratio

For M40 Grade concrete, w/c ratio can be taken as 0.45

Step 7: Determination of cement content

Based on the w/c ratio adapted, the cement content required for M40 Grade concrete is 386 kg/m$^3$.

Step 8: Determination of super plasticizer content

By trial and error, 0.4% of cement has been chosen and suitable deduction has been made in the water content. Hence water to be added is $w_w = 174 - (1-x) w_{sp}$

Step 9: Estimation of fine aggregate content.

Fine Aggregate content = \[1-\left[M_c/S_c + M_{ca}/S_{ca} + w_{w}/w + V_{ea}\right] \times S_{fa} \times 1000\] = 726 kg / m$^3$.

Step 10: Estimation of Copper Slag content

From the volume of FA obtained \[1-\left[M_c/S_c + M_{ca}/S_{ca} + w_{w}/w + V_{ea}\right]\], the natural river sand is reduced at 10% increment from 0 to 100% , and
weight of copper slag for each mix is obtained by multiplying by its specific gravity.

The quantity of each ingredient per m3 of concrete in each replacement level is given in Table 3.13.

A1.4 MIX DESIGN FOR M60 GRADE CONCRETE

Step 1: Determination of Target- mean strength

Based on the Table A1.1 of ACI 318 (3), the target mean compressive strength $f_{ck}$ is as follows

$$f_{ck} = f'_{ck} + 9.7$$

$$= 60 + 9.7 = 69.7 \text{N/mm}^2$$

Step 2: Selection of maximum size of coarse aggregate

The coarse aggregate confirm to graded aggregate of nominal size 12.5mm as per table 2 of BIS 383-1970 (36) is adopted. Also based on Table A.1.2 of ACI report 211.49.R3 (1), the size chosen is suitable for other grades viz M40 and M80.

Step 3: Determination of mixing water content

For M60 Grade concrete, the free water content chosen was 175 lits/m³

Step 4: Determination of air-content

From Table A.1.3 of ACI report 211.4R.93 (1), for nominal maximum size of coarse aggregate chosen (12.5mm), the approximate entrapped air content is 2%.
Step 5: Determination of coarse - aggregate content

As suggested by Aitcin(1998), coarse aggregate content as a function of typical particle shape, 1136 kg/m$^3$ has been selected for the M60 Grade concrete.

Step 6: Determination of w/c ratio

For M60 Grade concrete, w/c ratio can be taken, from the figure A1.1 as 0.35

Step 7: Determination of cement content

Based on the w/c ratio adapted, the cement content required for M60 Grade concrete is 500 kg/m$^3$.

Step 8: Determination of super plasticizer content.

By trial and error, 0.17% of cement has been chosen and suitable deduction has been made in the water content. Hence water to be added is $w_w = 175 - (1-x) w_{sp}$

Step 9: Estimation of fine aggregate content

Fine Aggregate content = $[1-[M_c/S_c + M_{ca}/S_{ca} + w_w/w + V_{ea}]] \times S_{fa} \times 1000$

= 519 kg / m$^3$.

Step 10: Estimation of Copper Slag content

From the volume of FA obtained $[1-[M_c/S_c + M_{ca}/S_{ca} + w_w/w + V_{ea}]]$, the natural river sand is reduced at 10% increment from 0 to 100%, and
weight of copper slag for each mix is obtained by multiplying by its specific gravity.

The quantities of each ingredient per m³ of concrete in each replacement level is given in Table 3.14.

A1.5 MIX DESIGN FOR M80 GRADE CONCRETE

Step 1: Determination of Target- mean strength

Based on the Table A1.1 of ACI 318 (3), the target mean compressive strength $f_{ck}$ is as follows

$$f_{ck} = f_{ck}' + 9.7$$

$$= 80 + 9.7 = 89.7 \text{N/mm}^2$$

Step 2: Selection of maximum size of coarse aggregate

The coarse aggregate confirm to graded aggregate of nominal size 12.5mm as per table 2 of BIS 383-1970 (36) is adopted. Also based on Table A.1.2 of ACI report 211.49.R3 (1), the size chosen is suitable for other grades viz M40 and M60.

Step 3: Determination of mixing water content

For M80 Grade concrete, the free water content chosen was 160 lits/m³.
**Step 4:** **Determination of air-content**

From Table A.1.3 of ACI report 211.4R.93 (1), for nominal maximum size of coarse aggregate chosen (12.5mm), the approximate entrapped air content is 2%.

**Step 5:** **Determination of coarse-aggregate content**

As suggested by Aitcin (1998), coarse aggregate content as a function of typical particle shape 1138 kg/m$^3$ has been selected for the M80 Grade concrete.

**Step 6:** **Determination of w/c ratio**

For M80 Grade concrete, w/c ratio can be taken, from the figure A1.1 as 0.295

**Step 7:** **Determination of Binder content.**

For M80 Grade HSC, to avoid higher cement content, Fly ash and Silica-fume has been added as supplementary cementitious materials. The Fly ash at 3% and Silica fume at 7% is added, i.e., 10% of cement /m$^3$ of concrete is replaced by the cementitious materials.

\[
\text{Binder content} = 160 \times 0.295 = 542 \text{ kg/m}^3
\]

\[
\text{Fly ash @ 3\%} = 542 \times \frac{3}{100} = 16 \text{ kg/m}^3
\]

\[
\text{Silica fume @ 7\%} = 542 \times \frac{7}{100} = 38 \text{ kg/m}^3
\]

\[
\text{Cement} = 542 - (16 + 38) = 488 \text{ kg/m}^3
\]
Step 8:  Determination of super plasticizer content

By trial and error, 0.6% of cement has been chosen and suitable deduction has been made in the water content. Hence water to be added is 

\[ w_w = 160 - (1-x) w_{sp} \]

Step 9:  Estimation of fine aggregate content

Fine Aggregate content = \[ [1-(M_c/S_c + M_{ca}/S_{ca} + w/w + V_{ca})] \times S_{fa} \times 1000 \]

\[ = 502 \text{kg/m}^3. \]

Step 10:  Estimation of Copper Slag content

From the volume of FA obtained \[ [1-(M_c/S_c + M_{ca}/S_{ca} + w/w + V_{ca})], \]
the natural river sand is reduced at 10% increment from 0 to 100% , and weight of copper slag for each mix is obtained by multiplying by its specific gravity.

The quantity of each ingredient per m3 of concrete in each replacement level is given in Table 3.15.