Mix Design Procedure for Lightweight Aggregate SCC (LWASCC) Based on the Wet Packing Method

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OUTLINE

INTRODUCTION

Lightweight Aggregate Self-Compacting Concrete (commonly termed as Self-Compacting Lightweight Concrete SCLC)

Experimental Program

Materials
Previous work done by the authors
Mix design methodology based on the optimum packing point concept

Ongoing work

Fiber-reinforced pumice aggregate self-compacting concrete

Future work
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LIGHTWEIGHT AGGREGATE SELF-COMPACTING CONCRETE (LWASCC)

A high performance material that combines the advantages of structural lightweight aggregate concrete (LWAC), such as:

- Reduced dead loads and formwork pressure
- High insulation capacity
- Improved durability
- Resistance against fire & chemical attack
- Self-compacting characteristics
Lightweight aggregate self-compacting concrete (LWASCC)

Arising challenges revolve around: mix design (more complex than for normal weight SCC), production procedure (handling of LWAs), cost minimization, market awareness (lack of widespread usage).
LIGHTWEIGHT AGGREGATE SELF-COMPACTING CONCRETE (LWASCC)

MAIN CONSIDERATIONS...

- Low weight (= low dynamic energy @ flow) → poor self-compactness
  - Are the terms ‘lightweight concrete’ & ‘self-compactness’ contradictory?
  - If not, do LWASCC fresh-state assessment scores fall into the typical range for normal weight SCC?
- Unfavorable difference in density between phases
  - How can the aggregates’ tendency for buoyancy be treated?
- High aggregates’ absorption capacity
- Mechanical properties
- Durability issues
LWASCC APPLICATIONS

Mainly in the precast industry

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LIGHTWEIGHT AGGREGATES: PUMICE

• Abundant reserves in Greece

• 2-3 times lighter than conventional (limestone) aggregates
  
  apparent density $\approx 600 \text{ kg/m}^3$
  
  particle density $\approx 1000 \text{ kg/m}^3$

• Low strength (crushing resistance $\approx 3.5 \text{ MPa}$)

• High Water Absorption (WA): 30-80% by weight
Pumice aggregate fractions

- **Sand**
  - 0-4 mm

- **Fine**
  - 4-8 mm

- **Coarse**
  - 8-16 mm

![Sieve size distribution graph](image)
Investigated methods for minimization of aggregates’ water absorption capacity

- **pre-wetting**
- **soaking**
  - sprinkling
  - immersion in water
  - coating after soaking
Investigated methods for minimization of aggregates’ water absorption capacity

<table>
<thead>
<tr>
<th>Water Absorption [%]</th>
<th>Saturation time [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse with stirring</td>
<td>+ 10 ~ 15%</td>
</tr>
<tr>
<td>Coarse without stirring</td>
<td></td>
</tr>
<tr>
<td>Fine with stirring</td>
<td></td>
</tr>
<tr>
<td>Fine without stirring</td>
<td></td>
</tr>
</tbody>
</table>

Soaking immersion in water
PUMICE AGGREGATE SELF-COMPACTING CONCRETE (PASCC) DESIGNED MIXTURES

Proportioning: based on the Okamura & Ozawa method

Aim: Assessment of the effect of Coarse-to-Fine (C/F) aggregates ratio

C/F MIX SERIES

\[ \rho_{\text{fresh}}: 1459 \sim 1523 \, \text{kg/m}^3 \]
\[ \rho_{\text{dry}}: 1365 \sim 1430 \, \text{kg/m}^3 \]

<table>
<thead>
<tr>
<th></th>
<th>kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement II 42.5</td>
<td>400</td>
</tr>
<tr>
<td>Sand</td>
<td>410</td>
</tr>
<tr>
<td>VMA</td>
<td>0.6</td>
</tr>
<tr>
<td>SP</td>
<td>5.0</td>
</tr>
<tr>
<td>Stabilizer</td>
<td>1.5</td>
</tr>
<tr>
<td>Efficient water</td>
<td>142</td>
</tr>
<tr>
<td>Coarse+Fine</td>
<td>380</td>
</tr>
</tbody>
</table>
C/F SERIES

Aggregate voids volume

- voids content: volumetric content of voids \([v]\) contained in an aggregate mixture
  \[v = \frac{(\rho_p - \rho_b)}{\rho_p} \times 100\]

- the least voids volume is related to the least attainable aggregate volume & it specifies the highest amount of excess paste in benefit of rheology

- the optimum C/F pumice aggregates ratio (70/30) from the workability tests was found to be in compliance with the C/F ratio corresponding to the least voids volume

\(\rho_p\): Particle density

\(\rho_b\): Bulk density
Specific strength by [14] ≈ 85% of mean specific strength (all LWASCC studies included)

Mean specific strength ≈ C35/45 NWC specific strength

1 out of 3 studies with natural LWAs
Optimum Packing Concept

- LWASCC mix proportioning method proposal
  (Optimum Packing Point – OPP concept)
  ✓ three separately investigated phases: paste, mortar & concrete
  ✓ use of the “wet packing method” for paste & mortar phases
    (+ standard consistency tests)
  ✓ evaluation of aggregate voids volume (as per EN 1097-3 & EN 1097-8)
  ✓ Definition of the optimum concrete phase proportions by adjusting
    the $K$ factor ($K = V_{\text{mortar}} / V_{\text{aggregates’ voids}}$)
“wet packing method” for paste & mortar phases

1. The weight ($w$) of a cement paste (or mortar) of given water-to-cementitious materials volumetric ratio ($u_w = V_w / V_{cm}$) is measured; the container of the paste (or mortar) is of known volume ($V_{total}$).

Optimized mixing procedure for pastes

(Wong & Kwan, 2008):

1. first, the entire water quantity is mixed with 1/2 of the cementitious materials + 1/2 of the SP for 3 minutes;

2. then, the rest of the cementitious materials and the SP are divided into four portions and each portion is added after an extra 3 minutes of mixing (total mixing time 15 minutes).
✓ “wet packing method” for paste & mortar phases

1. The weight \( w \) of a cement paste (or mortar) of given water-to-cementitious materials volumetric ratio \( u_w = V_w / V_{cm} \) is measured; the container of the paste (or mortar) is of known volume \( V_{total} \).

Optimized mixing procedure for mortars:

1. first, the entire water quantity is mixed with the pumice sand (for 1 min), then 1/2 of the cementitious materials + 1/2 of the SP are added and mixing continues for 3 minutes;

2. then, the rest of the cementitious materials and the SP are divided into four portions and each portion is added after an extra 3 minutes of mixing (total mixing time 16 minutes).
“wet packing method” for paste & mortar phases

2. Then, the contents of the total voids \( u \) and air voids \( u_\alpha \) (expressed as the voids-to-solid materials volumetric ratios) and the solid concentration \( \phi \), are calculated according to the following equations:

\[
V_{\text{solids}} = \frac{w}{\left[ \rho_w u_w + R_\alpha (3.1 + \rho_\beta R_\beta + \rho_\gamma R_\gamma + \rho_\delta R_\delta + \rho_{SP} R_{\text{Solids}_{-SP}} R_{SP}) \right]}
\]

**where:**
- \( R_\alpha \): Cement content as % of solids content, by vol.
- \( R_\beta, R_\gamma, R_\delta, R_{SP} \): Cementitious materials (\( \beta, \gamma \& \delta \)) & SP content as % of cement content, by vol.
- \( R_{\text{Solids}_{-SP}} \): Solids of SP as % of SP content, by vol.
- \( \rho_i \): Particle densities of each material

Total voids stand for the sum of air and water voids.

\[
u = \frac{(V_{\text{total}} - V_{\text{solids}})}{V_{\text{solids}}}
\]

\[
u_\alpha = \frac{(V_{\text{total}} - V_{\text{solids}} - V_w)}{V_{\text{solids}}}
\]

\[
\phi = \frac{V_{\text{solids}}}{V_{\text{total}}}
\]
✓ “wet packing method” for paste & mortar phases

Solid materials for pastes include: cementitious materials; sand powder (with max aggregate size < 125 μm); and admixtures’ solid contents.

In mortars solid materials also include: aggregates (with max aggregate size < 4 mm - mainly sand).

The procedure (in the paste phase) starts by selecting a rather high value of \( V_w / V_{cm} \) (e.g. 0.8), which is gradually reduced in a series of trial pastes until the measured solid concentration \( \varphi \) starts to decrease (or, equivalently, total voids \( u \) start to increase).

Further decrease of the \( w/cm \) ratio yields pastes that fail to form.
✓ “wet packing method” for paste & mortar phases
The investigation aimed at determining: (i) the proportions of powder materials in the paste; and (ii) the sand content, the SP dosage and the \( w/cm \) ratio in the mortar that yield the optimum packing in both phases.
✓ “wet packing method” for paste & mortar phases (+ standard consistency tests)

The optimum packing concept employed in this work is not associated to the maximum attainable solid concentration of the mixture ($\phi_{\text{max}}$);

It corresponds to the highest possible solid concentration that satisfies specific criteria associated to self-compactness ($\phi_{\text{opt}}$).

![Graph showing voids ratio vs. $V_w / V_{cm}$]
✓ “wet packing method” for paste & mortar phases (+ standard consistency tests)

**Pastes**
Desired Slump-Flow: 240 – 260 mm

**Mortars**
Desired Slump-Flow: 320 – 360 mm
Desired Flow Time: minimum possible

Slump-Flow (paste/mortar)  
mini V-funnel (mortar)
Paste mixes investigated (144 individual tests):

Single-additive (trial) mixture series

- Cement (CEM II 42.5 N)
- Limestone Filler LF$_{120}$ ($d_{\text{max}} = 120 \mu m$)
- Limestone Filler LF$_{10}$ ($d_{\text{max}} = 10 \mu m$)
- Silica Fume SF ($d_{\text{max}} = 1 \mu m$)

Notation:
- Control mixture: CEM
- Additive$_X\%$ (X: volumetric addition as cement replacement ≥12.5%, 25% & 50%)
  
  [SP content: 1.5% (by cement weight)]
Paste phase: single-additive (trial) mixture series
Paste mixes investigated (144 individual tests):

Multi-additive mixture series

Cement (CEM II 42.5 N) + Limestone Filler LF120 (d_{max} = 120 \mu m) + Pumice powder (d_{max} < 125 \mu m) + Silica Fume SF (d_{max} = 1 \mu m)

Notation:
- Control mixture: LF120
- LF120 _Third Additive_X% (X: % of cement by weight *5%, 8%, 10% & 15%)
  [SP content: 1.5% (by cement weight)]
  [total additive percentage was kept constant at 40% of cement volume]
Paste phase: multi-additive mixture series
Paste phase: multi-additive mixture series

Best multi-additive paste mixtures

- Water voids
- $LF_{120-LF_{15}}$
- $LF_{120-SF_{10}}$
- $LF_{10-SF_{8}}$

Properties:
- $f_{c_{28d}}$: 86.5 MPa
- $f_{f_{l28d}}$: 7.2 MPa
- $f_{c_{28d}}$: 93.5 MPa
- $f_{f_{l28d}}$: 10.4 MPa
Mortar phase:

- Two pastes for mortar mixes were used:
  - M1 comprising “LF\textsubscript{120-10-15}” paste
  - M2 comprising “LF\textsubscript{10-SF-8}” paste

\[\text{M1 or M2} + \text{Pumice sand (0 – 4 mm)}\]

- 40\% by CEM vol.
- 45\% by CEM vol.
- 50\% by CEM vol.
- SP: 1.5\% by CEM weight
- SP: 1.8\% by CEM weight
- SP: 2.1\% by CEM weight

18 mortar mix combinations (101 ‘wet packing method’ tests)
Mortar phase:

- **M1** comprises “LF$_{120}$-LF$_{10}$-15%” paste
- **M2** comprises “LF$_{10}$-SF-8%” paste
Mortar phase:

- M1 comprises “LF_{120-LF_{10}}_{15}” paste
- M2 comprises “LF_{10-SF_{8}}” paste
### Experimental Program - Optimum packing point concept

Prism cross-sections and flow spreads of different mortar mixtures

<table>
<thead>
<tr>
<th>Mortar Mixture</th>
<th>Compressive Strength ($f_{c_{28d}}$)</th>
<th>Flexural Strength ($f_{f_{l_{28d}}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1_PS40%_SP2.1%</td>
<td>67.7 MPa</td>
<td>7.6 MPa</td>
</tr>
<tr>
<td>M1_NS40%_SP2.1%</td>
<td>94.0 MPa</td>
<td>11.2 MPa</td>
</tr>
<tr>
<td>M2_PS40%_SP2.1%</td>
<td>77.9 MPa</td>
<td>8.6 MPa</td>
</tr>
<tr>
<td>M2_NS40%_SP2.1%</td>
<td>101.4 MPa</td>
<td>11.4 MPa</td>
</tr>
</tbody>
</table>

- **M1** comprises “LF$_{120}$_LF$_{10}$_15%” paste
- **M2** comprises “LF$_{10}$_SF_8%” paste
Concrete phase

So far:

✓ fines content (% by cement weight) ⇒ optimum paste
✓ sand content (% by cement weight)
✓ SP dosage (% by cement weight) ⇒ optimum mortar
✓ water content (% by cement weight)
✓ aggregates fractions’ ratio C/F that yields the least aggregates’ voids volume

Now:

*K* factor adjustment starting at \( K = 1.2 \)
Concrete phase [ **LF mixes** (comprising optimum mortar M1) ]

**L-box**

- Slump flow diameter classes:
  - Class SF1: 550 – 650 mm
  - Class SF2: 660 – 750 mm
  - Class SF3: 760 – 850 mm

- Passing ability classes – L-box:
  - PL1: $\geq 0.80$ with 2 rebars
  - PL2: $\geq 0.80$ with 3 rebars

**V-funnel**

- Viscosity classes V-funnel:
  - Class VF1: $< 9$
  - Class VF2: 9 - 25

**Graphs**:
- L-box passing ratio $[H_2/H_1]$ vs. Time [min]
- V-funnel [sec] vs. Time [min]
Concrete phase [ **SF mixes** (comprising optimum mortar M2) ]

### L-box passing ratio \( [H_2/H_1] \)

- **K = 1.55**
- **K = 1.4**
- **K = 1.35**

<table>
<thead>
<tr>
<th>Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>1.2</td>
</tr>
</tbody>
</table>

**V-funnel**

- **K = 1.55**
- **K = 1.4**
- **K = 1.35**

<table>
<thead>
<tr>
<th>Time [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>35</td>
</tr>
</tbody>
</table>

### Slump flow diameter classes.

<table>
<thead>
<tr>
<th>Class</th>
<th>Flow diameter in mm (Limit values for individual batches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SF1</td>
<td>550 - 650</td>
</tr>
<tr>
<td>SF2</td>
<td>660 - 750</td>
</tr>
<tr>
<td>SF3</td>
<td>760 - 850</td>
</tr>
</tbody>
</table>

### Passing ability classes – L-box.

<table>
<thead>
<tr>
<th>Class</th>
<th>L-Box ratio (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL1</td>
<td>( \geq 0.80 ) with 2 rebars</td>
</tr>
<tr>
<td>PL2</td>
<td>( \geq 0.80 ) with 3 rebars</td>
</tr>
</tbody>
</table>

### Viscosity classes V-funnel.

<table>
<thead>
<tr>
<th>Class</th>
<th>V-funnel time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VF1</td>
<td>( &lt; 9 )</td>
</tr>
<tr>
<td>VF2</td>
<td>9 - 25</td>
</tr>
</tbody>
</table>

**no retention**
Using Optimum Packing Point – OPP concept

- **without** OPP procedure
  - 400 kg/m³ cement
  - 30 kg/m³ limestone filler
  - 0.43 w/cm
  - ½ hour workability retention
  - LC 20/22 D 1.4

- **with** OPP procedure
  - 430 kg/m³ cement
  - 150 kg/m³ limestone filler
  - 0.32 w/cm
  - 1½ hour workability retention
  - LC 30/33 D 1.6
Using Optimum Packing Point – OPP concept

- **without OPP procedure**
  - 330 kg/m³ cement
  - 30 kg/m³ limestone filler
  - 60 kg/m³ silica fume
  - 0.41 w/cm
  - ½ hour workability retention
  - LC 20/22 D 1.4

- **with OPP procedure**
  - 380 kg/m³ cement
  - 90 kg/m³ limestone filler
  - 30 kg/m³ silica fume
  - 0.3 w/cm
  - 1 hour workability retention
  - LC 30/33 D 1.6
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Future work
2009-2010 RESEARCH

- **polypropylene fibers 25 mm**

- **polypropylene fibers 50 mm**

Fiber content: 0.5% by vol.
2009-2010 RESEARCH

▸ steel fibers 30 mm

▸ steel fibers 60 mm

Fiber content: 0.5% by vol.
Ongoing work – Fiber-reinforced PASCC


2009-2010 RESEARCH

- steel fibers 30 mm & NW sand
  - 1 hour retention

- steel fibers 30 mm, NW sand & silica fume addition
  - Fiber content: 0.5% by vol.
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Future work
2010-2011 RESEARCH

- Monotonic and cyclic pull-out tests on PASCC
- Shear & flexural tests on PASCC beams
- Textile Reinforced PASCC
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Thank you for your attention!