Abstract

Using non-traditional concrete in engineering applications such as the construction of nuclear reactor shields, dams, massive under water bridge piers and repairs of building foundations, is considered as an efficient solution to overcome challenges of limitations of the use of normal conventional concrete. Such new types of concretes which have been developed and produced are completely dissimilar from conventional concrete in that the method of mixing, handling, pouring, consolidation, behaviours and cost are different. Based on the technology of ready-mixed self-compacting concrete (SCC), two types of concrete have been introduced and named as: two-stage concrete (TSC) and rock-filled concrete (RFC), where a self-compacted grout (SCG) injected or poured to fill the void space of preplaced or self-compacted aggregate (SCA) or rocks. TSC is different from normal concrete (NC), in that it is made by first placing the coarse aggregate in the formwork and then injecting a grout consisted of sand, cement and water to fill the voids between the aggregate particles. The main benefits of the method include; Low heat of hydration, high compressive strengths and density, economic savings, practically no mass shrinkage, low coefficient of thermal expansion and excellent bond to existing structures [1-4]. Generally, the properties of two-stage concrete are thus influenced by the properties of the coarse aggregate, the properties of the grout, and the effectiveness of the grouting process. The two main objectives of this paper are: 1-describe the importance and the special requirements of introducing TSC to be used in the concrete industry and 2-present some results conducted in the last decade to address TSC in terms of: a) - obtaining a mortar that satisfies the optimal grout property requirements and b) – evaluation and modelling of some important mechanical properties.

Keywords: Two-Stage Concrete (TSC), Rock Filled Concrete (RFC), Self-Compacting Concrete (SCC), Mass Concrete Construction
shrinkage and consequently shrinkage cracking has been a growing concern. This has been the case in modern concrete work due to the use of higher content of cementitious materials, mineral admixtures, low water-to-cement ratio and extended exposure to severe conditions during service; all of which may contribute to increasing shrinkage in concrete. Minimizing shrinkage can take place by adequate mix proportions, thorough curing and the use of shrinkage compensating admixtures [5]. On the other hand, using non-traditional concrete in engineering applications has been considered as an efficient solution to overcome challenges of limitations of the use of normal conventional concrete. Such new types of concretes which have been developed and produced are completely dissimilar from the conventional concrete in the method of mixing, handling, pouring, consolidation, behaviours as well as cost.

TSC is produced through a two-stage process. Firstly washed coarse aggregate is placed into the formwork in-situ. Later a specifically designed grout is introduced into the form from the lowest point under gravity pressure to fill the voids, cementing the aggregate into a monolith [4], see Figure 1. Based on the technology of ready-mixed self-compacting concrete (SCC), two types of concrete been introduced and named as: two-stage concrete (TSC) and rock-filled concrete (RFC) [4]. In this paper we will consider the TSC in more details as will be seen below.

Figure 1. Self compacting grout technology

2. General Aspects of TSC

2.1. Advantages

TSC differs from conventional concrete in having higher percentage of coarse aggregates which are placed in direct contact with each other resulting in fewer voids that are to be filled with the mortar/grout. This low percentage of voids and direct contact of aggregate particles should have a positive impact on the concrete properties both on short and long terms. Its main advantages could be summarized as follows [4-6]:

- Less shrinkage leading to less cracking
- Easier placement in difficult placement conditions
- Adequacy for underwater construction and repair
- Super mechanical and durability properties
- Ability for placement at remote locations
- Good Environmental impact
- Reasonable cost

2.2. Technical Background

Mechanically TSC acts in a fundamentally different way under external stress to traditional concrete where the concrete matrix absorbs, distributes and resists the stresses. Due to this point-to-point contact in TSC all the stress is passed first through the stone skeleton then, after deformation of the stone particles, the grout both restrains the aggregate and transfers the loads as shown in Figure 2 [7].

The strength of TSC is a function of a number of variables, including the aggregate strength and the strength of the grout, in addition to other variables such as; water to cement ratio (w/c) and cement to sand ratio(c/s) [5].

Figure 2. Stress transfer mechanism in TSC

2.3. Applications of TSC

TSC is used where placing conventional concrete is extremely difficult, such as:

- Constructions include massive reinforcement steel and embedded items
- Underwater repairs.
- Concrete and masonry repairs, such as when spalling had occurred exposing the embedded reinforcement.
- Applications where shrinkage and heat of concrete must be kept to a minimum, such as dams.
- Applications where heavy weight aggregate used such as in the construction of nuclear reactors-shields.
- In large volume foundations where there are particular technical considerations such as concerns over thermal cracking, mass shrinkage and cold joints.
2.4. Materials Used

Similar to conventional concrete, the materials are: cement, sand, coarse aggregate, water, pozzolana additives, superplasticizer and fibres that comply with specifications can be used in TSC [4].

2.5. Grout Properties and Flow

The grout typically consists of sand, cement, water, pozzolana, plasticizer/super-plasticizer and air entraining agents (for anticipated freeze and thaw problem, if required). Good quality of TSC grout is characterised by high fluidity, low sedimentation, good viscosity, intensive hydration and a notable increase in the cement particles surface. The characteristics of the grout are affected by water content, sand grading and content, cement, pozzolana, and the types and amounts of super-plasticizer. For each mixture there are optimum amounts of fillers and superplasticizer which produce the best pumpability or consistency. The pozzolana and the plasticizer/super-plasticizer are used to impart flow-ability to the grout and acted on both the mechanical and rheological properties of the grout [8]. The injection is achieved by pumping the grout through vertically mounted rigid pipes which almost reach the bottom of the section to be cast. As the grout is pumped into the form the injection pipes are slowly raised. Injection of grout into small units can be achieved by pumping into the bottom of the formwork at different elevations [4]. Mathematically the description of propagation is very difficult. General empirical equation of propagation curve has been derived, [9], and described in Equation 1 as follows:

\[ y = \frac{\alpha}{(\beta x^2 + 1)^{\frac{1}{\gamma}} t + 1} \]

Where: \( \alpha \) = thickness of stone layer (m); \( \beta \) = (a \times b \times f); a = parameter dependent of mixture fluidity; \( b \) = parameter dependent of stone: shape, size, kind of grain, surface, number and relation of fraction; \( f \) = Environment of construction; \( \gamma = (c \times d \times e) \); \( c \) = parameter dependent of efficiency of flushing pipe (m³/min.); \( d \) = parameter dependent of perforation; \( e \) = parameter dependent on the kind of excavation bottom; \( t \) = time (min.); \( x \) = distance from flushing pipe (m); \( y \) = level of mixture in stone (m).

3. Experimental Investigations

3.1. Materials

The cement used was Portland cement Type I with 28-days compressive strength of 41 MPa and Blaine fineness of approximately 3500 cm²/g. Cement properties conformed to ASTM standards [10]. The fine aggregate used was natural beach sand of specific gravity 2.63 and maximum size of 1.18 mm. Coarse aggregate used was angular basalt of specific gravity 2.69, crushing value of 20.74%, abrasion value of 23.81%, and absorption value of 23.81%. Grading curves for both coarse aggregate and fine are presented in Figures 3 and 4, respectively. Both fine and coarse aggregate properties were found in accordance with ASTM standards [11]. The super plasticizer used in the grout was a naphthalene- formaldehyde derivative, trade name ‘SikaMent-163’ and was mixed at the rate of 2% by weight of cement. The expanding agent, trade name ‘Intraplast-Z’ was an aluminium powder-based admixture; this was also used at the rate of 2% by weight of cement.

3.2. Mixture Proportions and Sample Preparation

Three different proportions of sand –cement ratio (c/s), 0.5:1, 1:1 and 1.5:1, with varying water-cement ratios (w/c) of: 0.38, 0.55 and 0.80, were tried to determine the optimum mix proportions, as shown in Table 1. A total of 360 standard concrete cylinders (150mmx300mm) were tested in unconfined compression and tension at 28 days.

<table>
<thead>
<tr>
<th>w/c</th>
<th>c/s</th>
<th>cement Kg/m³</th>
<th>sand Kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38</td>
<td>0.5</td>
<td>295</td>
<td>590</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>421</td>
<td>421</td>
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<td></td>
<td>1.5</td>
<td>525</td>
<td>350</td>
</tr>
<tr>
<td>0.55</td>
<td>0.5</td>
<td>282</td>
<td>564</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>407</td>
<td>407</td>
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<td></td>
<td>1.5</td>
<td>338</td>
<td>338</td>
</tr>
<tr>
<td>0.8</td>
<td>0.5</td>
<td>265</td>
<td>530</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>396</td>
<td>396</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>490</td>
<td>326</td>
</tr>
</tbody>
</table>

4. Results

4.1 Consistency

To measure consistency, both a flow cone and flow table tests (on the mortar/grout) were conducted [12, 13] as shown in Figure...
5. Fluidity results are presented in Figure 6 and 7. Tests on consistency demonstrated that the higher c/s ratio of 1.5 required much more water, whereby the flow cone depends on the time of flow while the flow table depends on the propagation of flow [12]. For example, the w/c ratio 0.38 in the plain grout and expanding admixture at all c/s ratios is the minimum ratio to obtain grout; it was not possible to penetrate all voids in the aggregate skeleton and higher pumping pressure was required to inject the grout. As a result of low w/c and high c/s ratios, the concrete specimen has a honeycombed structure with partial binding of the aggregate skeleton. Grout containing superplasticiser at a w/c ratio of 0.38 and a c/s ratio of 1.5, on the other hand, filled visual voids and created a smooth surface of the sides and ends of each cylinder [14].

Figure 5. Flow cone and flow meter setup

![Figure 5. Flow cone and flow meter setup](image)

**Figure 6. Flow cone and flow meter setup**

![Figure 6. Flow cone and flow meter setup](image)  

**Figure 7. Flow cone and flow meter setup**

![Figure 7. Flow cone and flow meter setup](image)
4.2. Compressive Strength

The compressive strength \( fc' \) of TSC was tested with and without superplasticizer-admixture at 28 days. Sample of results is shown in Table 2. Based on the results, a relation for \( fc' \) has been assumed, according to the design algorithm presented [14]. Equation (2) is an empirical equation derived from the experimental data for prediction of compressive strength of TSC \( fc' \) as the following:

\[
fc' = A + B \cdot (w/c) + C \cdot (w/c)^2 + E \cdot (c/s) \tag{2}
\]

where: \( fc' \) represents the estimated compressive strength of TSC, \( w/c \) is the water-to-cement ratio and \( c/s \) is the cement-to-sand ratio. \( A, B, C, D \) and \( E \) are regression coefficients presented in Table 3.

Compressive strength without super-plasticizer was found to be lower than compressive strength with super plasticiser. The possible reason for this decrease in strength was the low fluidity of the grout. When high fluidity of grout was used (achieved by using super plasticiser at high \( w/c \) ratios), the compressive strength of TSC did not increase.

The quality of TSC depends not only on the strength of grout but on its ability to expand while fluid and remove the traces of bleed water that collect under aggregate particles [15,16]. With this idea of an expanding admixture, a blend of special metallic aluminium powder expansion agent was used in the grout.

The strength data, show that when using the expanding admixture the compressive strength of TSC was significantly increased. Super-plasticiser and expanding admixture were used together among the four types of grouts. The compressive strength was found to have the highest strength. This could be attributed to the following: (a) higher fluidity of grout using super plasticiser (which enables the grout to fill all the voids between aggregate particles) (b) expansion effect of grouts using expansion admixture to minimise bleeding and settlement of grout.

4.3. Tensile strength

The tensile strength \( ft \) of TSC was investigated at 28 days. Table 4 shows the values of experimental tensile strength in splitting mode.

Equation (3) is an empirical equation derived from the experimental data for prediction of tensile strength of TSC \( ft \) in (MPa).

\[
ft = A + B \cdot (w/c) + C \cdot (w/c)^2 + E \cdot (c/s) \tag{3}
\]

where, \( ft \) represents the estimated tensile strength of TSC, \( w/c \) is the water-to-cement ratio and \( c/s \) is the cement-to-sand ratio. Table 5 shows the values of the regression coefficients. No cause was apparent for the relatively high tensile strength.

However, it is believed that the amount of coarse aggregate, method of placement and the greater mechanical interlocking among the particles could be responsible for the high tensile strength. Failure in tension was restricted principally as a result of the line of fracture which was occurred through the mortar and coarse aggregate.

### Table 2. Average compressive strength results (MPa)

<table>
<thead>
<tr>
<th>Type of Grout</th>
<th>( w/c )</th>
<th>( s/c )</th>
<th>Without Adm.</th>
<th>Super-plasticiser</th>
<th>Expanding Admixture</th>
<th>Expanding Adm. &amp; Super-plasticisers</th>
</tr>
</thead>
<tbody>
<tr>
<td>( w/c )</td>
<td>( s/c )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.36</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>0.55</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>0.8</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Table 3. Regression results for equation (2)

<table>
<thead>
<tr>
<th>Type of Grout</th>
<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
<th>( D )</th>
<th>( E )</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Adm.</td>
<td>-3.7</td>
<td>11.2</td>
<td>3.96</td>
<td>-1.8</td>
<td>3.7</td>
<td>0.883</td>
</tr>
<tr>
<td>Super-plasticiser</td>
<td>43.9</td>
<td>-33</td>
<td>-3.3</td>
<td>-1.7</td>
<td>2.42</td>
<td>0.944</td>
</tr>
<tr>
<td>Expanding Admixture</td>
<td>-14</td>
<td>-40</td>
<td>68.5</td>
<td>0.47</td>
<td>2.63</td>
<td>0.891</td>
</tr>
<tr>
<td>Expanding Adm. &amp; Super-plasticisers</td>
<td>-26</td>
<td>-88</td>
<td>127</td>
<td>0.52</td>
<td>1.88</td>
<td>0.66</td>
</tr>
</tbody>
</table>

### Table 4. Average tensile strength results (MPa)

<table>
<thead>
<tr>
<th>Type of Grout</th>
<th>( w/c )</th>
<th>( s/c )</th>
<th>Without Adm.</th>
<th>Super-plasticiser</th>
<th>Expanding Admixture</th>
<th>Expanding Adm. &amp; Super-plasticisers</th>
</tr>
</thead>
<tbody>
<tr>
<td>( w/c )</td>
<td>( s/c )</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0.38</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2.18</td>
<td>2.44</td>
<td>2.61</td>
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<td>0.55</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2.42</td>
<td>2.66</td>
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<td>0.8</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2.36</td>
<td>2.58</td>
<td>2.82</td>
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### Table 5. Regression results for equation (3)

<table>
<thead>
<tr>
<th>Type of Grout</th>
<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
<th>( D )</th>
<th>( E )</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Adm.</td>
<td>-0.3</td>
<td>1.26</td>
<td>0.67</td>
<td>-1.3</td>
<td>0.51</td>
<td>0.833</td>
</tr>
<tr>
<td>Super-plasticiser</td>
<td>-13</td>
<td>-25</td>
<td>39</td>
<td>0.5</td>
<td>0.39</td>
<td>0.86</td>
</tr>
<tr>
<td>Expanding Admixture</td>
<td>-12</td>
<td>-23</td>
<td>36.1</td>
<td>0.52</td>
<td>0.48</td>
<td>0.96</td>
</tr>
<tr>
<td>Expanding Adm. &amp; Super-plasticisers</td>
<td>9.82</td>
<td>-7.4</td>
<td>-1.4</td>
<td>-1.4</td>
<td>0.42</td>
<td>0.855</td>
</tr>
</tbody>
</table>
4.4. Compressive-tensile strength relationship

From the results it appears that there is a good correlation between the compressive strength and tensile strength of TSC. As the compressive strength increased with grout, the tensile strength was also found to increase in the same manner. In the present work, however, Equation (4) was developed by regression analysis to relate tensile strength ($f_t$) to compressive strength ($f_c$). The relationship between the compressive strength and the tensile strength of different grout proportions is shown in Figures 8 to 11 for different admixtures.

$$f_t = A + (B) \times f_c + (C) \times (f_c)^D$$  (4)

Where: $f_t$ is tensile strength and $f_c$ is the compressive strength. Table 6 shows the values of the regression coefficients.

5. CONCLUSIONS

- As the method of placement in TSC is entirely different from that of NC, a suitable super-plasticizer is necessary to satisfy the requirement for the pumping ability of grout. The expanding super-plasticizer was found to be the most suitable super-plasticizer as it provided higher fluidity with minimum bleeding.
• The compressive strength and tensile strength of TSC was tested with and without super-plasticizer at 28 days for all grout proportions. On the basis of the results, a correlation between the strength and grout proportions was statistically derived.

• The fractured specimens of TSC showed that a large proportion of failures occurred by cracking through the coarse aggregate particles.

• The authors believe that there are many aspects of TSC that require clarification through further theoretical and experimental studies such as: energy dissipation, failure mechanism and cracking, shrinkage, creep and other time dependent deformations.

6. REFERENCES

[3]. ACI Committee 318 “Building code requirements for reinforced concrete” American Concrete Institute, Detroit, Michigan, USA, (2008).