Incorporation of Crushed Sands and Tunisian Desert Sands in the Composition of Self Compacting Concretes
Part I: Study of Formulation

Abdelhamid Rmili,1,2) Mongi Ben Ouezdou,1) Mhamed Added,3) and Elhem Ghorbel4)

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Abstract: This paper examines the incorporation of the crushed sand (CS) and desert sand (DS) in the formation of self compacting concrete (SCC). These sands have been substituted for the rolled sand (RS), which is currently the only sand used in concretes and which is likely to run out in our country. DS, which comes from the Tunisian Sahara in the south, is characterized by a tight distribution of grains size. CS, a by-product of careers containing a significant amount of fines up to 15%, is characterized by a spread out granulometry having a maximum diameter of around 5 mm. These two sands are considered as aggregates for the SCC. This first part of the study consists in analyzing the influence of the type of sand on the parameters of composition of the SCC. These sands consist of several combinations of 3 sands (DS, CS and RS). The method of formulation of the adopted SCC is based on the filling of the granular void by the paste. The CS substitution to the RS made it possible, for all the proportions, to decrease the granular voids, to increase the compactness of the mixture and to decrease the water and adding fillers proportioning. These results were also obtained for a moderate substitution of DS/CS (< 40%) and a weak ratio of DS/RS (20%). For higher proportions, the addition of DS to CS or RS did not improve the physical characteristics of the SCC granular mixture.

Keywords: self compacting concrete, desert sand, crushed sand, rolled sand, granular packing, formulation.

1. Introduction

In Tunisia and in most African countries, only rolled sands (RS) are currently used in the manufacture of concrete.1 The use of crushed sands (CS), a by-product of the massive rocks quarries, is very rare in constructions and is limited to some road constructions.1 Moreover, most of these countries suffer from an important lack of suitable aggregates. However, these countries contain inexhaustible quantities of desert dune sands which were never put to use seriously in constructions.

At the end of the 20th century, a new generation of concrete was born: self compacting concretes (SCC). These SCC, extremely fluid, require for their composition, a high percentage of sand and fillers. The control of their composition requires a constant development of their formulation, a rigorous control of their rheological properties and a perfect knowledge of the characteristics of their constitutive materials.2,3

The incorporation of the CS, which contains important fines proportion and which has a granulometry spread out, can bring a solution for the composition of the SCC. In the same way, desert sands (DS), which have a very fine granulometry, can allow for an increase in the compactness of the granular mixture of the SCC. This DS sand may constitute a local material of construction in the sub-Saharan regions. Some research projects focusing on the use of the river Dune sand and sea sand, similar to the DS, into the formulation of concrete, has been carried out by Bederina et al.4,5 Moreover, an attempt has been presented by Zhang et al.6 to study the performance of concrete made by Teggei DS.

This paper deals with the study of the SCC formulation based on granular packing and the filling of the intergranular void by a binder paste. Several sand combinations are compared with the mixtures optimized so as to analyze the influence of the sand type on the formulation parameters of the SCC. These mixed granular are based on sand combinations of CS, RS and DS. The latter has been obtained from the Tunisian desert (south of Tunisia). The second part of this paper will present the results of the rheological at the fresh state and the mechanical strength at the hardened state of these SCC.

2. Identification of the constitutive materials of the studied SCC

2.1 Aggregates

Rolled sand (RS): The RS is extracted from a quarry of siliceous movable rock located at the North-East of Tunisia. Its
chemical and physical characteristics are given in Tables 1 and 4. It is a 0/2.5 mm sand having a low content of fine (grain < 0.08 mm) of about 1.80%.

- Crushed sand (CS): The CS comes from a calcareous quarry of rock in the north-east of Tunisia. Its chemical and physical characteristics are given in Tables 2 and 4. It has a continuous granulometry being spread out from 0.08 to 5 mm and a fine content of about 12.44%.

- Desert sand (DS): DS comes from the Tunisian Sahara desert of the south near the town of Kebili (south of Tunisia). Its chemical and physical characteristics are in Tables 3 and 4. The composition shows that this sand is silico-calcareous. It is a mono sand granular very fine of maximum granulometry of 0.4 mm and content of fine of about 14.4%.

- Gravel (G): The gravel comes from the same quarry as that of the CS. Its physical granulometry and its characteristics are presented in Fig. 1 and Table 4. It has a granulometry being spread out from 4 to 16 mm.

2.2 Binders and additions
- Cement (C): It is a Portland cement of the type CEM I 42.5 in conformity with Tunisian Standard NT 47.01. These physical characteristics are as follows: a Specific density of 3.1 and a Blaine specific surface of 440 m²/kg. Its granulometry is illustrated by Fig. 2.
- Filler (F): The used filler is the product of crushing of a calcareous rock, which comes from the center of Tunisia. Its physical characteristics are as follows: size range: 0/0.112 with 96.6% < 0.080 mm, a density of 2.739 and a Blaine specific surface of 460 m²/kg. Its chemical composition and its granulometry are presented in Table 5 and Fig. 2.
- Admixture (A): The employed admixture is a superplasticizer (SP), a high water reducer of new generation and not chloride based on acrylic copolymer (Viscocrete-Tempo12, produced by “Tunisian SIKA”). Its physicochemical characteristics are given in Table 6.

3. Study of formulation

Several methods of SCC formulation are proposed in the literature. They are different in their design but they all lead to similar compositions. The adopted formulation method in this study is based on the filling of the intergranular voids by the binder paste in order to have a maximum compactness and to guarantee a good behavior of SCC material.

3.1 Comparison of the considered formulation methods

The method of formulation considered for the composition of the studied SCC is based on a method known to be a Chinese

<table>
<thead>
<tr>
<th>Table 1 Chemical characteristics of RS.</th>
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<tbody>
<tr>
<td>RS  SiO₂  Fe₂O₃  Al₂O₃  CaO  MgO  Na₂O  K₂O  TiO₂  Ignition loss</td>
</tr>
<tr>
<td>%  98.26  0.11  0.34  0.08  0.01  0.03  0.17  0.002  1.024</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2 Chemical characteristics of the CS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS  CaO  Fe₂O₃  Al₂O₃  MgO  Na₂O  SiO₂  SO₃  Ignition loss</td>
</tr>
<tr>
<td>%  54.892  0.523  0.035  0.436  0.049  0.436  0.192  42.32</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3 Chemical characteristics of the DS.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS  SiO₂  CaCO₃  SO₄  CT  Total gypsum  Insoluble residues  Soluble salts</td>
</tr>
<tr>
<td>%  92.05  4.58  0.94  0.1  1.68  89.36  1.28</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4 Physical characteristics of the aggregates.</th>
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</thead>
<tbody>
<tr>
<td>Finesses modulus, FM</td>
</tr>
<tr>
<td>Fines &lt; 80 µm (%)</td>
</tr>
<tr>
<td>Absorp. coeff., CAB (%)</td>
</tr>
<tr>
<td>Sand equivalent, SE (%)</td>
</tr>
<tr>
<td>Loose density, LD (kg/m³)</td>
</tr>
<tr>
<td>Absolute density, AD (kg/m³)</td>
</tr>
<tr>
<td>Max diameter, Dmax (mm)</td>
</tr>
<tr>
<td>RS  1.73  1.80  0.25  7.50  1.612  2.659  2.5</td>
</tr>
<tr>
<td>CS  3.01  12.44  0.30  78.26  1.580  2.699  5</td>
</tr>
<tr>
<td>DS  0.38  14.40  2.30  61.50  1.366  2.562  0.4</td>
</tr>
<tr>
<td>G   0.30  0.30  1.397  2.705  16</td>
</tr>
</tbody>
</table>

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It consists in piling up aggregates (sand and gravel) and filling up the granular voids with paste. Proportionings of the aggregates were calculated according to their loose densities, of the sands/aggregate ratio and of the packing factor. However, the method known as the Japanese method suggests that the proportioning of the gravel in the mixture of concrete corresponds to 50% of its packed density and the proportioning of sand in the mortar corresponds to 50% of its packed density. Furthermore, the method known as the French method passes by an optimization of the porosity of the system formed by all the solid matter constituents. It is based on the modeling of the behavior of the concrete in a fresh state from the calculation of the compactness of its granular skeleton. It goes through the determination of the properties of the components by calculating the maximum compactness of the aggregates via the compressible packing model (CPM) and by using the Rene-LCPC software. The water/binder ratio is calculated according to the standard (EN 206-1) for a volume of paste of about 370 liters. Proportionings in admixtures were adjusted by rheological tests in the fresh state. Optimization is made by the “Concrete Lab Pro2” software and by using the packing and shearing models and by applying the necessary requirements. In this study, the Rene LCPC software was used for the determination of the optimal packing of the three sands combined two to two (Fig. 3). The packing of various sands with the gravel was not optimized in order to study the effect of the type of sand on the granular arrangement of the mixture. Moreover, the sand/aggregate voluminal ratio was fixed at 0.5.

The Rene-LCPC software, developed at the Laboratoire Central des Ponts et Chaussees in France, is based on the CPM. This model, considered as an ideal tool of predicting the compactness of a granular packing, allows the minimization of the porosity or the maximization of the compactness of the granular skeleton of a mixture by optimizing the proportions of the various size ranges. The data input necessary for each mixture are: granulometry, density, the index of tightening and real compactness. The main results are the proportions of the size ranges and the corresponding porosities. The drawing of the porosity curve as a function of the aggregates proportion allows thus to obtain the optimal porosity and the maximum compactness and to deduce the optimal granular combination.

Water proportioning necessary for cement and filler is based on the condition of fluidity according to the method described by Domone and Wen. However, in the Chinese, Japanese and French methods, water was given according to the current standard which generally depends on the foreseeable strength of the concrete.

The proportioning of the filler is calculated by the method known as the Dutch method, which is based in its turn on the Chinese method and consists in drawing the quantity from the filler based on one cubic meter of SCC including all confused.

Cement proportionings were generally taken according to the country standards and the necessary requirements. The air content

Fig. 2 Granulometry curves of the cement and fillers. These analyses were performed by laser granulometry.

Table 6 Physicochemical characteristics of the superplasticizer (A).

<table>
<thead>
<tr>
<th>Viscocrete tempo 12</th>
<th>Density (1.06 ± 0.01)</th>
<th>pH (6 ± 1)</th>
<th>Na₂Oeq(%) (1)</th>
<th>Dry extract(%) (30.2 ± 1.3)</th>
<th>CT(%) (0.1)</th>
</tr>
</thead>
</table>

Fig. 3 Packing of the sands.

(a) Packing RS and CS
(b) Packing CS and DS
(c) Parking RS and DS
varies from 1 to 3% in the ordinary SCC for all the methods.

### 3.2 Determination of the aggregates proportioning

The granular mixture consists of gravel and a variation of three sands. The proportions of the sands optimal mixtures, combined between them, are determined by the CPM (through the Rene LCPC Software).

The optimal proportions are given on the curves of Fig. 3. The optimal packing of sands gave the following combinations:

- 30% of RS and 70% of CS (Fig. 3(a)),
- 15% of DS and 85% of CS (Fig. 3(b))
- the packing of the DS and the RS did not show a net minimum. The porosity increased linearly with the DS. This increase indicated that the DS has not improved the compactness of the mixtures because of their high finesses.

In addition to these optimal mixtures, other combinations were added in order to take into account of the technical-economic factor (Table 7). The sand mass ($M_{S}$) and the gravel mass ($M_{G}$) are calculated by the following Eq. (1):

$$M_{S} = PF \times LD_{S} \times \frac{V_{S}}{V_{a}}, \quad M_{G} = PF \times LD_{G} \times \left( 1 - \frac{V_{S}}{V_{a}} \right)$$

where:
- $PF$ : packing factor, the ratio of mass of aggregates in the mixture to that of loosely packed state according to ASTM C-29,
- $LD_{S}$ : sand loose density,
- $V_{S}/V_{a}$ : volume ratio of fine aggregates to total aggregates, which ranges from 50% to 57%,
- $LD_{G}$ : gravel loose density.

### 3.3 Determination of water proportioning

The calculation of water proportioning is based on the fluidity condition of the binder paste. The water needed for each powder follows from flow spread tests with the Haegermann flow cone, executed analogously to Domone and Wen.

The results are presented on Fig. 5. For various water/powder ratios, the relative slump $R_{p}$ was determined by the following Eq. (2):

$$R_{p} = \left( \frac{d}{d_{0}} \right)^{2} - 1$$

where $d$: flow diameter in mm and $d_{0}$ the lower diameter of the cone (= 100 mm).

The water mass $M_{W}$ is given by the Eq. (3):

$$M_{W} = (a_{c} R_{p} + b_{c}) M_{C} + (a_{p} R_{p} + b_{p}) M_{F}$$

Table 7 Combinations of sands of the studied SCC.

<table>
<thead>
<tr>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>C9</th>
<th>C10</th>
<th>C11</th>
<th>C12</th>
<th>C13</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS (%)</td>
<td>100</td>
<td>30</td>
<td>50</td>
<td>70</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>60</td>
<td>80</td>
</tr>
<tr>
<td>CS (%)</td>
<td>0</td>
<td>70</td>
<td>50</td>
<td>30</td>
<td>100</td>
<td>85</td>
<td>70</td>
<td>55</td>
<td>40</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DS (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>15</td>
<td>30</td>
<td>45</td>
<td>60</td>
<td>100</td>
<td>60</td>
<td>40</td>
</tr>
</tbody>
</table>

sent on Fig. 5(a). $M_{C}$ and $M_{F}$ are the masses of cement and filler respectively.

### 3.4 Determination of proportioning in superplasticizer

The SP mass $M_{SP}$ is given by the Eq. (4):

$$M_{SP} = n(\rho_{C} V_{C} + \rho_{F} V_{F})$$

where “n” is the SP proportioning, $\rho_{C}$ and $\rho_{F}$ are the absolute densities of cement and the filler, respectively, and $V_{C}$ and $V_{F}$ are their volumes.
The volume of the dry extract of SP, \( V_{SP} \), is given by the Eq. (5):

\[
V_{Sp} = \frac{m_{Sp} \cdot M_{Sp}}{\rho_{Sp}}
\]  

(5)

where \( m_{Sp} \), \( \rho_{Sp} \), and \( M_{Sp} \) are the content of the dry extract, its density and the mass of the SP respectively.

### 3.5 Cement proportioning and of air void contents

Cement proportioning was taken equal to 350 kg/m³ by considering that the studied SCC were concretes with prescribed specifications of current strengths and exposed to a moderate environment (ENV 206.1 Standard). The air void volume in the SCC was estimated at 1.5% by considering that, in Tunisia, the freezing weather is very rare.

### 3.6 Determination of the content of filler

One m³ of SCC is generally made up of the volumes of Gravels (\( V_{G} \)), sands (\( V_{S} \)), cement (\( V_{C} \)), fillers (\( V_{F} \)), water (\( V_{W} \)), superplasticizer (\( V_{SP} \)) and air void (\( V_{air} \)), as presented by Eq. (6):

\[
1m^3 (SCC) = V_C + V_S + V_C + V_F + V_W + V_{SP} + V_{air}
\]  

(6)

The paste volume is written as presented by Eq. (7):

\[
V_{paste} = V_C + V_F + V_W + V_{SP} + V_{air}
\]  

(7)

However, this paste volume (\( V_{paste} \)) must at least fill out the aggregates void volume (\( V_{Agg} \)), packed in one m³ of SCC (Eq. (8)):

\[
V_v = 1m^3 (SCC) - V_{Agg}
\]  

(8)

By introducing the terms of Eqs. (3, 4, 5, 6 and 8) into the Eq. (7), the voluminal proportioning of the filler becomes as the following (Eq. (9)):

\[
V_F = \frac{V_v - V_{air} - V_C \left(1 + a_CR_p + b_C + \frac{m_{Sp} \cdot M_{Sp}}{\rho_{Sp}}\right)}{1 + a_FR_p + b_F + \frac{m_{Sp} \cdot M_{Sp}}{\rho_{Sp}}}
\]  

(9)

where \( a_C \) and \( b_C \) (resp. \( a_F \) and \( b_F \)) are the terms of the right-hand sides of the line equation relative to cement (resp. filler) presented on Fig. 5(b).

### 3.7 Composition of the studied SCC

The composition of the SCC of this study is based on the following data:

- A Packing Factor PF equal to 1.18,
- A volume ratio of fine aggregates to total aggregates equal to 0.50,
- A relative slump equal to 1.

The water proportioning was corrected, \( M_{w,corr} \), by cutting off the fraction from water brought by the SP and by adding the water absorbed by the aggregates (Eq. 10).

\[
M_{w,corr} = (a_C R_p + b_C) M_C + (a_F R_p + b_F) M_F + (1 - m_{Sp}) M_{Sp} + C_{Ab,G} M_{G} + C_{Ab,S} M_{S}
\]  

(10)

where \( C_{Ab,G} \) and \( C_{Ab,S} \) are the water absorption coefficients of the gravel and sands (Table 4).

By referring to the method of formulation suggested above, Table 8 presents the theoretical composition of the SCC to be studied. In addition to the physical characteristics of the granular components, this table contains also the volume of the intergranular voids, the filler quantity and the water proportioning calculated for various contents of superplasticizer (\( n = 0.7, 1, 1.3 \) and 1.5%).

### 4. Interpretations

The formulations obtained show that sand proportioning depends on their apparent loose densities. The sand mass decreases with its density, such as in the case of the SCC containing uncombined sands (C1, C5 and C10) and the SCC containing the desert sand (C9, C11 and C12). Furthermore, for these latter SCC the intergranular voids volume and the gravel/sand ratio are high (\( V_V > 0.35 \) and \( G/S > 0.9 \)). The effect of this result might cause problems of flow and SCC implementation. However, the SCC based on the other combined sands contains high sands mass and moderate \( V_V \) and \( G/S \) (Table 8).

The combination of sands has induced an increase in the loose densities (LD) and consequently the reduction in intergranular voids (\( V_V \)) and an increase in the aggregates volume (\( V_{Agg} \)) (Fig. 6). This result has also been found in the case of the sand concrete. The increase in LD by 4.65% (resp. 6.77%) was reached compared to the optimal combination (C4) of RS (resp. of CS). This increase is from 4.05 to 20.35% (resp. 1.74 to 20.05%) for CS and DS (resp. for RS and DS) with respect to C6 (resp. C13) combination. This figure shows also that a reduction of \( V_V \) by 4% (resp. 7.38%) was obtained compared to the optimal combination (C4) of RS (resp. of CS). Furthermore, this decrease is from 1.5 to 5.12% (resp. 2.12 to 2.42%) for SC and DS (resp. for RS and DS).

The packing of these various sands had also caused the increase in the absolute sands densities and thus the increase in the sands and the aggregates masses (Fig. 7). This increase requires only low filler proportioning resulting in a decrease in water demand and generating higher mechanical strengths as observed by Ayed et al., while using local materials in the SCC study.

High volumes of the intergranular voids required large quantities of fillers for their filling as described by many researchers. Indeed, the studied SCC based on the uncombined sand had required high quantities of fillers (about 210 kg of filler for the DS, 170 kg for the CS and 150 kg for RS). However, the contents of filler are the lowest for the optimized formulations (\( \approx 135 \) kg for C4, \( \approx 147 \) kg for C6 and \( \approx 143 \) kg for C13). Water proportioning follows the same order because it depends amongst other things on the content of fillers. These results are shown for example on Fig. 8 for 1% of SP (Fig. 8).

### 5. Conclusions

This study showed that the adopted method for the SCC formulation allowed the calculation of the majority of the compo-
The sand combination having a varied granulometry had a positive effect on the granular arrangement of the SCC. The packing of several sands allowed a compactness increase of the granular mixture and a reduction in the intergranular voids. Consequently, the reduction of this volume led to a moderate content of the added filler and to a lower important water proportioning.

Crushed sand, which naturally encloses important contents of fines (10 to 18%) and whose grains are angular contributes to the improvement of the packing of the granular mixtures in the SCC. The loose density was improved between 4.65 and 20.35% for the combined sands compared with sands alone. In the same way, intergranular voids volume decreased between 1.5 to 7.38% for combined sands. The moderate incorporation of the

<table>
<thead>
<tr>
<th>Table 8 Theoretical composition of the SCC for various sand combinations and superplaticizer proportionings.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCC code</td>
</tr>
<tr>
<td>Ms (kg)</td>
</tr>
<tr>
<td>RS (kg)</td>
</tr>
<tr>
<td>CS (kg)</td>
</tr>
<tr>
<td>DS (kg)</td>
</tr>
<tr>
<td>Sand AD</td>
</tr>
<tr>
<td>RS (kg)</td>
</tr>
<tr>
<td>CS (kg)</td>
</tr>
<tr>
<td>DS (kg)</td>
</tr>
<tr>
<td>Aggregate AD</td>
</tr>
<tr>
<td>V_{c} (m³)</td>
</tr>
</tbody>
</table>

Fig. 6 Looses densities and aggregates volumes and their voids for various sands combinations: R: RS, C: CS, and D: DS.

Fig. 7 Absolutes densities and masses of sands and of the aggregates for various sands combinations.

Fig. 8 Filler and water masses for various sands combinations for 1% of SP.
desert sand as a partial substitution of the crushed sand and rolled sand allowed increasing the compactness of the mixture. The optimal compactness increased by 15.5% by combining the crushed sand with the desert sand with respect to the crushed sand.

The second part of this work (part II) will consist in studying the effect of these various combinations of sands on the SCC characteristics of the in the fresh and hardened state.

Acknowledgments

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References