A Study on Using Crushed Sand to Replace Natural Sand in High-Strength Self-compacting Concrete Towards Sustainable Development in Construction

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Abstract. In recent years, the use of natural sand to produce concrete has led to increased demand for sand quarrying, resulting in this valuable resource exhaustion. Therefore, there should be synchronous solutions to limit the use of resources that are gradually depleted, contributing to environmental protection. One of the solutions is to use crushed sand to replace natural sand as aggregate in concrete, especially the study of using crushed sand to make high-strength self-compacting concrete. Crushed sand is an aggregate of angular shape and surface roughness that hinders the self-compacting of the concrete mixtures. Combination with fine mineral admixtures will be a good solution to improve the rheological properties of the concrete, i.e. reducing the internal friction between the angular particles in the paste system, increasing the ability to "lubricate" the aggregate particles, thereby creating excellent workability and self-compacting ability for concrete with slump flow of 820 mm and flow time of 4.5s, the ability to flow through reinforcing steel meets the technical requirements of EFNARC and compressive strength at the age of 28 days reaches over 85 MPa.

1. Introduction
Self-consolidating concrete (SCC) is a relative new class of high-performance concrete that is able to flow and consolidate under its own weight, completely fill the formwork even in the presence of dense reinforcement, whilst maintaining homogeneity, and without the need for any additional compaction [1-5]. The using of SCC also supports the green construction through the cement reducing and reducing the use of vibrator that requires not less energy. Besides, SCC can reduce the price of concrete by reducing the worker and speed up the production time [6]. With the shortage of natural sand resources in the world, the study of crushed sand replacing natural sand as an aggregate has been increasing, especially in countries where demand strong construction such as China, India, and so on. There have been many studies relating to the use of crushed sand in making concrete [7-10]. Shen et al. studied on ultra-high-strength concrete using crushed sand based on its shape and surface properties, and many types of mineral admixtures such as silica fume, fly ash, blast furnace slag [8, 11]. Research results show that the introduction of crushed sand can easily to make high-strength concrete with a high slump from 18.5 to 22 cm due to the surface properties of this sand. The compressive strength of concrete can be achieved from 114 to 122 MPa, from 138 to 150 MPa at the age of 7 and 28 days, respectively [7, 12, 13]. In fact, the use of crushed sand as a fine aggregate has gradually increased in concrete industry due to the supplying shortage of natural (river) sand and the growing restrictions to get natural sand for environmental protection. However, up to now, crushed sand is only used to produce non-fired building materials, precast spun concrete such as water pipes, concrete piles and concrete pavements [13, 14]. Moreover, the study of high-strength self-compacting concrete (HS-SCC)
is less interested than that of conventional concrete or high performance concrete. Therefore, this paper focuses on the use of crushed sand replacing natural sand to make high-strength self-compacting concrete.

2. Materials and methods

2.1 Materials

2.1.1 Cement. In this study, cement PC40 But Son was used with the properties given in Table 1:

| No. | Characteristics                          | Test method            | Unit    | Result |
|-----|-----------------------------------------|------------------------|---------|--------|
| 1   | Specific gravity                        | TCVN 4030:2003         | g/cm³   | 3.09   |
| 2   | Fineness (retained material on the No.009 sieve) | TCVN 4030:2003         | %       | 0.4    |
| 3   | Consistency                             | TCVN 6017:2015         | %       | 27.0   |
| 4   | Setting time:                           |                        |         |        |
|     | - Initial                               | TCVN 6017:2015         | Min.    | 120    |
|     | - Final                                 |                        | Min.    | 210    |
| 5   | Compressive strength:                   |                        |         |        |
|     | - At 3 days                             | TCVN 6016:2011         | MPa     | 24.3   |
|     | - At 28 days                            |                        | MPa     | 44.7   |

Cement PC40 But Son meets technical requirements of Vietnamese standard TCVN 2682:2009.

2.1.2 Fly ash. The mineral admixture used in this study is fly ash, type F. The properties of fly ash are shown in Table 2 and Table 3.

| No. | Characteristic                          | Test Method | Unite  | Value |
|-----|-----------------------------------------|-------------|--------|-------|
| 1   | Specific gravity                        | TCVN 4030:2003 | g/cm³  | 2.28  |
| 2   | Fineness (retained material on the No.0045 sieve) | ASTM C618-15 | %      | 0     |
| 3   | Strength activity index                 | TCVN 8825:2011 | %      | 80.4  |
|     | - 7 days                                |              | %      | 84.2  |
|     | - 28 days                               |              | %      |       |

Table 3. The chemical properties of fly ash

| Oxyde     | CaO  | MgO   | Fe₂O₃ | Al₂O₃ | SiO₂  | L.O.I  | SO₃   | TiO₂  | Na₂O  |
|-----------|------|-------|-------|-------|-------|--------|-------|-------|-------|
| Content (%)| 0.40 | 1.00  | 5.59  | 23.74 | 58.50 | 4.61   | 0.1   | 0.42  | 3.84  |

The fly ash with the above physical, mechanical, and chemical properties meet technical requirements of ASTM C618-03.

2.1.3 Crushed and natural sands. The crushed limestone was used as artificial sand in this study, which meets technical requirements of Vietnamese standard TCVN 9205:2012. Besides, a natural (river) sand was also used in order to compare with crushed sand in make HS-SCC. The particle size distribution of natural sand was adjusted to be the same as that of crushed sand. The properties of this sand are given in Table 4:
Table 4. Properties of crushed sand and natural (sand used in the study)

| No. | Characteristics                           | Test method       | Unit   | Result Crushed sand | Result Natural sand |
|-----|------------------------------------------|-------------------|--------|----------------------|---------------------|
| 1   | Specific gravity                         | TCVN 7572:2006    | g/cm³  | 2.75                 | 2.68                |
| 2   | Density (dry condition)                  | TCVN 7572:2006    | g/cm³  | 2.70                 | 2.65                |
| 3   | Density (SSD condition)                  | TCVN 7572:2006    | g/cm³  | 2.72                 | 2.66                |
| 4   | Absorption                               | TCVN 7572:2006    | %      | 0.9                  | 0.3                 |
| 5   | Bulk density                             | TCVN 7572:2006    | g/cm³  | 1.73                 | 1.63                |
| 6   | Passing material on the No.0075 sieve     | TCVN 7572:2006    | %      | 7.63                 | 2.12                |

2.1.4 Coarse aggregate - Crush stone. Two crushed limestones were used as coarse aggregate with different sizes, i.e. (5-10) mm and (10-20) mm. The properties of crush stone meet technical requirements of Vietnamese standard TCVN 7570:2006, shown in Table 5.

Table 5. Properties of crushed stone used in this study

| No. | Characteristics                           | Test method       | Unit   | Result |          |
|-----|------------------------------------------|-------------------|--------|--------|----------|
| 1   | Specific gravity                         | TCVN 7572:2006    | g/cm³  | 2.75   |          |
| 2   | Density (dry condition)                  | TCVN 7572:2006    | g/cm³  | 2.70   |          |
| 3   | Density (SSD condition)                  | TCVN 7572:2006    | g/cm³  | 2.72   |          |
| 4   | Absorption                               | TCVN 7572:2006    | %      | 0.5    |          |
| 5   | Bulk density:                             |                   |        |        |          |
|     | - Type (5-10) mm                         | TCVN 7572:2006    | g/cm³  | 1.36   |          |
|     | - Type (10-20) mm                        |                   | g/cm³  | 1.41   |          |
| 6   | Flaky, elongated content                 | TCVN 7572:2006    | %      | 9.1    |          |

2.1.5 Superplasticizer. The polycarboxylate ether superplasticizer with the active solids content of 33.33% was used in this study.

2.2 Methods
This paper focuses on the influence of crushed sand on properties of self-compacting concrete following the EFNARC guideline [3] and ACI 237R-07 [2], i.e. workability, compressive strength. The V-funnel test to BS EN 12350-9 is used to assess the viscosity and filling ability of self-compacting concrete. Time taken by concrete to flow out of the funnel is recorded as the V funnel flow time T0. Stability of the mix is determined by measuring the time needed to empty the funnel completely 5 minutes after filling. This time is referred to as T5. Segregation of the mix is reasonable if the difference between T0 and T5 is less than or equal to 3 sec.

The slump-flow and T500 time is a test to assess the flowability and the flow rate of self compacting concrete in the absence of obstructions. The result is an indication of the filling ability of self compacting concrete. The T500 time is also a measure of the speed of flow and an indication of the viscosity of the self-compacting concrete.

The fresh concrete is poured into a cone as used for slump test. When the cone is withdrawn upwards the time from commencing upward movement of the cone to when the concrete has flowed to a diameter of 500 mm is measured; this is the T500 time. The largest diameter of the flow spread of the concrete and the diameter of the spread at right angles to it are then measured and the mean is the slump-flow.
The L-Box test to BS EN 12350-10 is used to assess the passing ability of self-compacting concrete to flow through tight obstructions without segregation or blocking. The apparatus consists of an L-shaped box. The time for concrete to reach points 20 cm (T20) and 40 cm (T40) down the horizontal portion of the box is recorded. After the concrete comes to rest in the apparatus, the heights of the concrete at the end of the horizontal portion, H2, and in the vertical section, H1, are measured. The blocking ratio, H2/H1 should be 0.80 to 0.85.

To evaluate the effect of crushed sand on the properties of the SCC, Central Composite Design - CCD with a combined mixture-process model was chosen. The mixture constraints for the binder components (Z1, Z2, Z3) were also chosen:
- Z1: the water to binder ratio, by vol.: from 0.845 to 0.853.
- Z2: the fly ash content, by vol.: from 15% to 25%.
- Z3: the aggregate content, by vol.: from 53.66% to 57.69%.

Twenty-designed mixtures of SCC were given in Table 6. That response surface experimental plan would be satisfactory to represent the effects of the mixture components on slump test (SF, mm), flowing time (T500, s), and compressive strength at 28 days (R28, MPa).

| N°  | Coded variable | Real variable |
|-----|----------------|---------------|
| CP1 | -1 -1 -1       | 0.845 0.15    | 53.66 |
| CP2 | +1 -1 -1       | 0.853 15      | 53.66 |
| CP3 | -1 +1 -1       | 0.845 25      | 53.66 |
| CP4 | +1 +1 -1       | 0.853 25      | 53.66 |
| CP5 | -1 -1 +1       | 0.845 15      | 57.69 |
| CP6 | +1 -1 +1       | 0.853 15      | 57.69 |
| CP7 | -1 +1 +1       | 0.845 25      | 57.69 |
| CP8 | +1 +1 +1       | 0.853 25      | 57.69 |
| CP9 | -1.682 0 0     | 0.842 20      | 55.68 |
| CP10| +1.682 0 0     | 0.856 20      | 55.68 |
| CP11| 0 -1.682 0     | 0.849 11.59   | 55.68 |
| CP12| 0 +1.682 0     | 0.849 28.41   | 55.68 |
| CP13| 0 0 -1.682     | 0.849 20      | 52.29 |
| CP14| 0 0 +1.682     | 0.849 20      | 59.07 |
| CP15| 0 0 0          | 0.849 20      | 55.68 |
| CP16| 0 0 0          | 0.849 20      | 55.68 |
| CP17| 0 0 0          | 0.849 20      | 55.68 |
| CP18| 0 0 0          | 0.849 20      | 55.68 |
| CP19| 0 0 0          | 0.849 20      | 55.68 |
| CP20| 0 0 0          | 0.849 20      | 55.68 |

In order to study the use of crushed sand for concrete, many authors [4, 6, 10] have studied the optimum sand/aggregate ratio through packing density of granular mixtures. The maximum packing density will lead to the highest strength of the concrete system. On the other hand, because the maximum packing density, the space between the aggregate particles is minimized, thus, the amount of excess paste to "lubricate" will be maximized. This leads to the best workability of concrete mixtures. Based on experimental results on packing density and calculated porosity of granular mixtures, the ratio of crushed stone (5-10) mm and (10-20) mm of 40/60 wt% was chosen. Besides,
the ratio of crushed sand and coarse aggregate of 60/40 wt% was also chosen. Based on these ratios, the concrete mixtures were designed, the results are presented in Table 7.

Table 7. Concrete mixtures used in experimental plan

| No. | Concrete mixture proportioning (kg/m³) |
|-----|--------------------------------------|
|     | Cement  | Fly ash | Crushed sand | Crushed stone (5-10 mm) | Crushed stone (10-20 mm) | Water | Superplasticizer |
| CP1 | 660     | 86      | 885          | 236                   | 354                  | 212   | 6.71             |
| CP2 | 657     | 86      | 885          | 236                   | 354                  | 213   | 6.68             |
| CP3 | 582     | 143     | 885          | 236                   | 354                  | 212   | 6.53             |
| CP4 | 579     | 142     | 885          | 236                   | 354                  | 213   | 6.50             |
| CP5 | 602     | 78      | 952          | 254                   | 381                  | 194   | 6.13             |
| CP6 | 600     | 78      | 952          | 254                   | 381                  | 195   | 6.10             |
| CP7 | 531     | 131     | 952          | 254                   | 381                  | 194   | 5.96             |
| CP8 | 529     | 130     | 952          | 254                   | 381                  | 195   | 5.93             |
| CP9 | 595     | 110     | 919          | 245                   | 367                  | 203   | 6.34             |
| CP10| 590     | 109     | 919          | 245                   | 367                  | 204   | 6.29             |
| CP11| 655     | 63      | 919          | 245                   | 367                  | 204   | 6.46             |
| CP12| 530     | 155     | 919          | 245                   | 367                  | 204   | 6.17             |
| CP13| 638     | 118     | 863          | 230                   | 345                  | 219   | 6.80             |
| CP14| 547     | 101     | 975          | 260                   | 390                  | 188   | 5.83             |
| CP15| 593     | 109     | 919          | 245                   | 367                  | 204   | 6.32             |
| CP16| 593     | 109     | 919          | 245                   | 367                  | 204   | 6.32             |
| CP17| 593     | 109     | 919          | 245                   | 367                  | 204   | 6.32             |
| CP18| 593     | 109     | 919          | 245                   | 367                  | 204   | 6.32             |
| CP19| 593     | 109     | 919          | 245                   | 367                  | 204   | 6.32             |
| CP20| 593     | 109     | 919          | 245                   | 367                  | 204   | 6.32             |

3. Results and Discussion

3.1 Influence of crushed stone on workability of SCC mixtures

Experimental results on workability of SCC, i.e. slump flow, T500, passing ability (Lbox) of SCC mixtures were given in Table 8.

The results show that when the aggregate content increases, the flow time decreases but when exceeding a certain value, flow time increases. It is possible to explain this phenomenon because when the aggregate content is not large enough, when the amount of aggregate increases, it can be considered each particle when moving as a "mini stirring wing", the number of stirrers increased to reduce the viscosity of the cement paste; However, when the amount of aggregate exceeds a specified value, the space between the aggregate particles decreases. This will increase the internal friction between the particles, thus, the viscosity of the concrete mixture increases, the flow time increases. Furthermore, when the water/binder ratio increases, the flow time decreases but when the value exceeds a certain value, the flow time increases. This is caused when the ratio of water to binder increases, the thickness of water between the particles in the system increases, thus, the "lubrication" of water between these particles increases, which leads to a decrease of internal friction and viscosity of concrete mixture. However, when the water to binder exceeds a certain value, the thickness of the water between the particles exceeds the amount of water required by the particles. This will cause the
segregation of concrete mixtures, and the aggregate settling down obstructs the flow of HHBT, thus, the flow time increases.

Similarly, as the fly ash content increases, due to the spherical shape of the fly ash, internal friction between the particles decreases, the viscosity and the flow time of the system decrease. However, when the volume of fly ash exceeds a certain value (approximately 20% by volume of binder), this will cause the segregation of concrete mixture, resulting to increasing the flow time of concrete mixture.

Beside the evaluation of slump flow and flow time of SCC mixtures, the passing ability of some SCC mixtures was also determined. The experimental results show that it is possible to completely make SCC from crushed sand which satisfies the technical requirements on passing ability of EFNARC [3].

3.2 Influence of crushed sand on compressive strength of SCC

Experimental results of compressive strength of SCC at the ages from 3 to 28 days was given in Table 8. From the data presented in Table 9, the regression function of the compressive strength at 28 days was established (the coefficients were tested as significant by the Student standard):

$$R_{28} = 85.398 - 0.883x_1 - 0.782x_2 + 0.664x_3 + 1.771x_1x_2 + 1.021x_1x_3 + 1.269x_2x_3 - 4.615x_1^2 - 3.349x_2^2 - 4.014x_3^2$$

By checking with the Fisher standard, it is easy to see that the function corresponds to the experiment. By determining the maximum value of the mathematical function, the function has a maximum value of 85.55 MPa at $[x_1, x_2, x_3]$ equal to $[-0.116; 0.164; 0.092]$, respectively.

Based on the results of the designed SCCs using the Central Composite Design (CCD) method, the

| N°  | Coded variable | Workability | Compressive strength |
|-----|----------------|-------------|----------------------|
|     | $X_1$  | $X_2$  | $X_3$ | SF (mm) | T500 | Lbox | R$_{3\text{days}}$ (MPa) | R$_{7\text{days}}$ (MPa) | R$_{28\text{days}}$ (MPa) |
| CP1 | -1    | -1    | -1    | 780   | 10.3  | 0.71 | 57.2  | 65.2  | 75.7  |
| CP2 | 1     | -1    | -1    | 800   | 5.85  | 0.86 | 51.8  | 60.5  | 69    |
| CP3 | -1    | 1     | -1    | 830   | 5.5   | 0.88 | 51.3  | 61.2  | 71.3  |
| CP4 | 1     | 1     | -1    | 850   | 7.25  | 0.77 | 56.3  | 63    | 74.3  |
| CP5 | -1    | -1    | 1     | 750   | 8.2   | 0.72 | 60.3  | 77.3  | 76.3  |
| CP6 | 1     | -1    | 1     | 790   | 6.05  | 0.83 | 59.7  | 68    | 76.3  |
| CP7 | -1    | 1     | 1     | 840   | 4.65  | 0.95 | 46.7  | 61    | 69.5  |
| CP8 | 1     | 1     | 1     | 830   | 8.45  | 0.74 | 52.8  | 60.7  | 74    |
| CP9 | -1.682| 0     | 0     | 845   | 7.85  | 0.76 | 63.5  | 71.7  | 76.3  |
| CP10| 1.682 | 0     | 0     | 835   | 5.45  | 0.9  | 56.3  | 60.3  | 68.7  |
| CP11| 0     | -1.682| 0     | 740   | 7.35  | 0.73 | 56.7  | 65.8  | 76.8  |
| CP12| 0     | 1.682 | 0     | 790   | 5.25  | 0.77 | 45.8  | 55    | 75.3  |
| CP13| 0     | 0     | -1.682| 825   | 5.75  | 0.94 | 62.3  | 62.7  | 68.7  |
| CP14| 0     | 0     | 1.682 | 790   | 6.45  | 0.75 | 58.8  | 68    | 77.5  |
| CP15| 0     | 0     | 0     | 810   | 4.5   | 0.95 | 68.2  | 74.2  | 86    |
| CP16| 0     | 0     | 0     | 815   | 4.25  | 0.96 | 67.7  | 73.2  | 84.7  |
| CP17| 0     | 0     | 0     | 810   | 4.75  | 0.97 | 67.5  | 75.2  | 85.7  |
| CP18| 0     | 0     | 0     | 820   | 4.6   | 0.97 | 68.8  | 74.2  | 85    |
| CP19| 0     | 0     | 0     | 815   | 4.55  | 0.95 | 67.5  | 76.8  | 86    |
| CP20| 0     | 0     | 0     | 805   | 4.85  | 0.92 | 67.8  | 77.5  | 85    |

Table 8. Workability and compressive strength of SCC mixtures
values of \([x_1, x_3, x_3]\) equal to \([-0.237, 0, -0.062]\) were selected as the optimal mix. Based on this optimal mix, the substitution of natural sand with a same particle size with 50\% and 100\% crushed sand by volume was carried out (Table 9). The experimental results on slump flow, flow time and compressive strength at the age of 3 days, 7 days and 28 days are presented in Figures 1 to 3.

**Table 9.** Concrete mixtures using crushed sand and natural sand

| Components (kg/m\(^3\)) | SCC using 100\% crushed sand | SCC using 50\% crushed sand and 50\% natural sand | SCC using 100\% natural sand |
|--------------------------|-------------------------------|-----------------------------------------------|-------------------------------|
| Cement (kg/m\(^3\))     | 593.8                         | 593.8                                         | 593.8                         |
| Fly ash (kg/m\(^3\))    | 109.5                         | 109.5                                         | 109.5                         |
| Crushed sand (kg/m\(^3\)) | 916.7                        | 458.3                                         | 0                             |
| Natural sand (kg/m\(^3\)) | 0                             | 441.7                                         | 883.3                         |
| Crushed stone (5 - 10) mm (kg/m\(^3\)) | 244.4                  | 244.4                                         | 244.4                         |
| Crushed stone (10 - 20) mm (kg/m\(^3\)) | 366.7                  | 366.7                                         | 366.7                         |
| Water (kg/m\(^3\))      | 204.2                         | 204.2                                         | 204.2                         |
| Superplasticizer (kg/m\(^3\)) | 6.33                         | 6.33                                         | 6.33                         |

**Figure 1.** Slump flow of SCCs using crushed and natural sands

**Figure 2.** Flow time T500 of SCCs using crushed and natural sands

**Figure 3.** Compressive strength of SCCs using crushed and natural sands with time
Based on the experimental results, the effect of the angular shape of crushed sand on the properties of SCC mixtures can be clearly seen. This is a significant difference of the slump flow and flow time T500 of mixtures using crushed and natural sands because of the internal friction of the particle system. On the other hand, due to the angular shape of the crushed sand, the bonding between crushed sand particles and cement paste is higher than that of natural sand. The difference between the experimental results between the SCCs containing 100% and 50% artificial sands is negligible.

4. Conclusion
Based on the experimental results of the study on the use of crushed sand replacing natural sand as the fine aggregate for self-compacting concrete, some conclusions can be withdrawn as below:

- The use of crushed sand to make SCC with the slump flow of 820 mm, flow time of 4.5s, the passing ability, compressive strength of over 85 MPa at 28 days to meet technical requirements of EFNARC is entirely feasible.
- The effect of crushed sand on the SCC mixtures and hardened SCCs in comparable with natural sand was studied. There is a large difference between the workability of SCC mixtures using crushed and natural sands, i.e. the lower T500 flow time and higher slump flow of mixture using crushed sand. The compressive strength of the SCC using crushed sand is significantly higher than that of SCC using natural sand.

5. References
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