International Conference on Sustainable Design, Engineering and Construction

Optimization of gradation and fineness modulus of naturally fine sands for improved performance as fine aggregate in concrete

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Abstract

Sand is an accumulation of grains of mineral matter derived from the disintegration of rocks. It is distinguished from gravel only by the size of the grains or particles. Sand deposits of varying gradation are available in different regions of the world. The prime use of sand, as fine aggregate is in the manufacture of concrete. As fine aggregate comprises up to 30% of the total volume of concrete, consequently gradation and fineness modulus of sand are among principal factors affecting the performance of fresh and hardened concrete. For the purpose of this study, eight sand deposits were selected from various regions of Pakistan. The grain size distribution was compared with the ASTM gradation limits recommended for concrete. It was revealed that only two sands satisfy the ASTM gradation limits while all the others do not comply being on the finer side. For betterment of the construction industry, a sand optimization technique was developed. The optimization phase consisted of sieving the crusher fines and mixing different fractions of crusher fines with the natural sand in different combinations to get desired sand gradation. The optimized gradation curves matched with the ASTM limits and the optimized fineness modulus reached within the ASTM limits. The concrete made with optimized sands showed up to 39% increase in compressive strength. The composition of mineral constituents was also evaluated through x-ray diffraction and x-ray fluorescence, which indicated that the fine aggregate having higher silica content resulted in concrete with higher strength as compared to the one with higher calcium content. It was concluded that fine graded sands could be used in concreting after optimization that will reduce the huge transportation costs of using coarse sand from far-flung areas.

Keywords: Sand; Fine Aggregate; Fineness Modulus; Concrete; ASTM; Crusher fines; Compressive Strength

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Peer-review under responsibility of the organizing committee of ICSDEC 2016
doi:10.1016/j.proeng.2016.04.016
1. Introduction

Sand is a naturally occurring granular material composed of finely divided rock and mineral particles. Usually commercial sand is obtained from river beds or from sand dunes originally formed by the action of winds. The usual particle size of sand grains is between 0.075 mm to 4.75 mm with further subdivision of coarse sand in range of 2 mm to 4.75 mm, medium sand in range of 0.42 mm to 2 mm and fine sand in between 0.075 mm to 0.42 mm [1].

The prime use of sand is in the manufacture of concrete as a fine aggregate. Concrete is a mixture of Portland cement, water, course aggregate and fine aggregate. Natural sand is commonly used as fine aggregate, which usually comprises up to 30 percent of the total volume of concrete. Consequently, characteristics of sand significantly affect the performance of fresh and hardened concrete and have an impact on the cost effectiveness of concrete [2]. Gradation or particle size distribution of sand affects the properties of concrete like packing density, voids content, workability and strength [3]. Uniformly distributed mixtures generally lead to higher packing resulting in concrete with higher density and less permeability, and improved abrasion resistance. Consequently, uniformly distributed mixtures require less paste, thus decreasing bleeding, creep, and shrinkage [4,5]. If fine aggregate is too coarse it will produce bleeding, segregation and harshness, but if it is too fine, the demand for water will be increased [6]. All of these factors affect the strength of hardened concrete.

Fuller and Thompson first evaluated the significance of aggregate gradation in concrete proportioning in 1908 [7]. They developed an ideal gradation curve based on maximum density. Talbot and Richart conducted further advancement on aggregate gradation based on density in 1923[8]. Subsequently, several other aggregate gradation concepts evolved including optimizing surface area, fineness modulus, minimizing particle interference and others. Modern concepts pertaining to aggregate gradation that have recently evolved include Shilstone method of workability and coarseness charts [9].

Donza et al. conducted research on high strength concrete with different fine aggregates and found that concrete with crushed stone sand results in higher strength than the corresponding natural sand concrete at all test ages. They also concluded that the shape and texture of crushed sand particles have an important effect on the interlocking of paste and aggregate particles, leading to an improvement of strength of concrete [10].

Divya Haritha and her team evaluated the use of crushed rock as fine aggregate in high strength concrete in comparison to the natural fine aggregate and concluded that the crushed rock as fine aggregate gives improved compressive strength of concrete. The split tensile strength of concrete also increases when fine aggregate is completely replaced with crushed rock [11].

Various sand deposits exist in different regions of Pakistan and there is a general trend to use coarser sand from Northern region, which involves high transportation costs. There was a need to reduce the dependency on specific sand deposit by improving the gradation and strength properties of locally available sands. This study focuses on evaluation of effects of grain size distribution, fineness modulus and mineral constituents of various types of sands on strength of hardened concrete. In addition, development of an optimization technique to improve the grain size distribution and fineness modulus of fine graded sands thereby enhancing the strength properties of hardened concrete. Eight sand deposits were selected and were evaluated for their gradation properties and percentages of mineral constituents through X-ray diffraction analysis (XRD) and X-ray fluorescence test (XRF). The majority of sand types were found fine graded and unsuitable for concreting works as defined by ASTM standards. The finer sands were optimized by adding different fractions of crusher fines and were re-evaluated for strength properties of hardened concrete.

2. Objectives

• Evaluate the effects of gradation, fineness modulus and mineral constituents of various natural sands on strength of hardened concrete.
• Develop an optimization technique to optimize the grain size distribution and fineness modulus of fine sands and to make them suitable for concreting works.
• Evaluate the optimized sands in improving the gradation, fineness modulus and strength of hardened concrete.
3. Methodology

- Identification of sand deposits and collection of samples.
- Analysis of engineering and material properties with emphasis on grain size distribution, fineness modulus and mineralogical constituents composition.
- Comparison of strength properties of natural sands in concreting.
- Development of a technique for optimization of sand gradation of fine sands.
- Evaluation of the optimized sands for improvement in strength properties of hardened concrete.

4. Test results and discussions

4.1. Comparison of gradation with ASTM gradation limits

Eight major sand deposits were selected and designated as S-1 to S-8. Samples were collected from each sand deposit. The comparative results of all the sands with the ASTM gradation limits, as given in ASTM C-33 [12] are shown graphically in Fig. 1. All the sands were finer than the ASTM gradation limits except S-6 and S-8. The S-8, sand was the best match to the ASTM gradation limits while S-6 was a little finer than S-8.

4.2. Fineness modulus

The results show that there is a wide variation in the values of fineness modulus of different sands. Only two of the sands, i.e. S-6 and S-8 satisfy the ASTM fineness modulus criteria of 2.3 to 3.1 [12]. The rest of the 6 sands do not comply to ASTM criteria and are on the finer side having fineness modulus value ranging from 0.69 to 1.8.

![Fig. 1. Sand gradation versus ASTM gradation limits.](image)

4.3. Absorption percentage

Absorption capacity or percentage absorption represents the maximum amount of water the sand sample can absorb. All the sand samples were tested for their absorption percentage in saturated surface dry (SSD) condition according to the ASTM C-128 [13]. All the sands have absorption less than 3%, which is the limiting range for fine aggregates for concreting. The S-8 sand has the lowest absorption percentage, i.e. 1.75% being the coarsest sand of all types while the S-6 sand has the highest absorption percentage of 2.11%, but it is also within range of the acceptable limit.
4.4. Soundness test values

The Sodium sulfate soundness test was conducted according to the specifications of the ASTM C 88 [14]. The acceptable limit for sands according to the ASTM C-33-03 is up to 10% after five cycles of the test. The soundness test value of all the sand samples was less than 10%, which is the acceptable limit according to the ASTM C-33-03. All the sand samples were found suitable for concreting purposes according to this test.

4.5. Mineral compound characteristics by x-ray diffraction test

The results showed that all the sand samples had the major mineral component as silica in the form of silica oxide except S-6 and S-5 sands, which had major mineral component as calcium in the form of calcium silicate.

4.6. Mineral composition by x-ray florescence

All the sands generally followed the same trend with high percentage of silica and lower percentage of calcium except S-6 and S-5 sands, which contained higher percentage of calcium. The behavior of S-6 and S-5 sands should be evaluated being high in calcium content and low in silica content. The results of this test confirmed the results of XRD. The comparison of four major constituents is shown in Fig. 2.

4.7. Evaluation of natural sands in concrete

4.7.1. Concrete mix

The concrete mixes were prepared using all of the eight different sand samples and remaining variables as constant with the cement: fine aggregate: coarse aggregate ratio of 1: 2: 4 (by weight), respectively, cement content of 201.7 kg/m³ (12.59 lb/ft³) and water-to-cement ratio of 0.5 with constant slump value. The course aggregate used, was taken from Margallah quarry located in the Northern region of Pakistan. The cement used was type 1, Portland cement.

4.7.2. Workability of fresh concrete

The workability was evaluated by measuring the slump of fresh concrete according to the ASTM C-143 [15]. The slump values of the concrete made with different types of sands ranged between 28 to 30 mm (1.1 to 1.2 inch) with same water-to-cement ratio. This slump value was taken as constant for further compressive strength testing of hardened concrete.
4.7.3. Compressive strength of concrete cylinders and cubes

The test was conducted on 4x4 inch cubes as per the BS-1881 and 4x8 inch cylinders as per the ASTM C-39 [16, 17]. The compressive strength was determined at the age of 3, 7, 14 and 28 days [18, 19]. The compressive strengths of concrete cubes and cylinders follow the same trend line thus confirming the results. The comparative results of compressive strength of concrete cylinders are graphically shown in Fig. 3. The S-8 sand proved to be the best fine aggregate giving highest compressive strength of 23860 Kpa (3463 psi). Gradation meeting the ASTM specifications, lowest percentage of micro fines and within range fineness modulus of S-8 sand are the supporting factors for the highest compressive strength. The trend of gradation of different sands as compared with the ASTM gradation limits is also confirmed by the results of the compressive strength. The S-2, S-3 and S-4 sands are below 20684 Kpa (3000 psi) which is not desirable for concreting works.

5. Optimization technique to optimize performance of fine sands

Various types of sands had different gradation and varying fineness modulus where as other engineering properties were within limits of the ASTM standards as discussed previously. The ASTM limits of gradation and standard value of fineness modulus for sand to be used as fine aggregate in concreting works were being followed for the optimization program. It was evident from the results that S-6 and S-8 satisfy the ASTM standards so the remaining six sands were considered for optimization process.

5.1. Potential for optimization

The optimization potential means the percentage improvement that can be achieved by using any optimization technique. The variables considered in the optimization program were the gradation and the fineness modulus. Both of these variables were to be kept within the ASTM limits. As a result, various types of sands had different optimization potential based on their gradation and value of fineness modulus. The summary of optimization potential based on fineness modulus is tabulated in Table 1.

5.2. Optimization technique

Having observed the gradation and fineness modulus of various sands, an endeavor was made to bring them within the specified limits of the ASTM by adding a fraction of coarse material. The crusher fines were taken and various fractions were produced by sieving the crusher fines on number 4, 8, 16, 30 and 50 sieves and retrieving the fractions retained on these sieves. These fractions were denoted as R4, R8, R16, R30 and R50.
Table 1. Comparison of optimization potential based on fineness modulus.

| Sand Source | Original Fineness Modulus | Potential Fineness Modulus | Optimization Potential |
|-------------|---------------------------|----------------------------|------------------------|
| S-1         | 1.45                      | 2.6                        | 44.23%                 |
| S-2         | 1.04                      | 2.6                        | 60.00%                 |
| S-3         | 0.69                      | 2.6                        | 73.46%                 |
| S-4         | 0.7                       | 2.6                        | 73.07%                 |
| S-5         | 1.47                      | 2.6                        | 43.46%                 |
| S-7         | 1.94                      | 2.6                        | 25.38%                 |

5.3. Optimization methodology

- Different percentages of various fractions of crusher fines were added to the sand samples and optimized samples were produced.
- The optimized samples were than tested for their gradation and fineness modulus to satisfy the ASTM limits of the two variables.
- The optimized samples were then used for making concrete cubes and cylinders thus determining the improvement in the compressive strength of concrete specimens.

5.4. Combinations of sand and crusher fines mix

Various fractions of crusher fines were added to the original sand samples in various percentages and optimized sand samples were than tested for the improved gradation and improved fineness modulus. These improved versions of results were then compared with the ASTM specified limits. Various different combinations were tried for making the optimized sand samples. The details of the best mix are tabulated in Table 2.

Table 2. Summary of best mix of sand and crusher fines.

| Sand Type | % of Sand | % of Crusher Fines | % of Fractions of Crusher Fines |
|-----------|-----------|--------------------|---------------------------------|
|           |           |                    | R4 | R8 | R16 | R30 | R50 |
| S-1       | 50        | 50                 | 10 | 24 | 22  | 22  | 22  |
| S-2       | 40        | 60                 | 8  | 4.2| 20  | 40  | 27.8|
| S-3       | 31.6      | 68.4               | 4.6| 5.7| 20.2| 29.9| 39.4|
| S-4       | 30        | 70                 | 4.8| 10.7|12.3 | 29.4| 42.8|
| S-5       | 46        | 54                 | 1.2| 8.5 |22.2 | 29.8| 38.3|
| S-7       | 57        | 43                 | 8.3| 8.3 |33.3 |16.8| 33.3|

5.5. Optimization results

5.5.1. Optimized fineness modulus

The optimized sand samples were evaluated for their fineness modulus. The results are tabulated in Table 3. It became evident that the fineness modulus value of all the sands increased after optimization and all of the values falls within ASTM limiting range of 2.3 to 3.1.
5.5.2. Improved gradation

The optimized sand samples were evaluated for their gradation and the results were compared with the ASTM limits of gradation. The summary of results is shown in Fig. 4. The comparison clearly shows that the gradation curves of optimized sands are satisfying the ASTM gradation limits where as the original ones were out of the limits.

5.5.3. Optimized compressive strength of concrete

The optimized sand samples were tested by making concrete specimens and determining the improved compressive strength at the age of 3, 7, 14 and 28 days. These improved strengths were then compared with the original compressive strength values to get the percentage improvement and the results are shown in Fig. 5. The results show that there is significant improvement in the compressive strengths and all the optimized sands are above 20684 Kpa (3000 psi), which is the foremost requirement for a sand to be used in concreting works.

Table 3. Summary of optimized fineness modulus.

| Sand Type | Original Fineness Modulus | Optimized Fineness Modulus |
|-----------|--------------------------|---------------------------|
| S-1       | 1.45                     | 2.62                      |
| S-2       | 1.04                     | 2.36                      |
| S-3       | 0.69                     | 2.31                      |
| S-4       | 0.7                      | 2.35                      |
| S-5       | 1.47                     | 2.32                      |
| S-7       | 1.94                     | 2.58                      |

Fig. 4. Comparison of optimized gradation curves with ASTM limits.

6. Conclusion

- Six out of eight sand types do not comply with the ASTM standards and therefore they might be unsuitable for concreting works.
- Fine graded (unsuitable) sands can be optimized by adding different percentages of various fractions of crusher fines to get improved gradation, improved fineness modulus and increased compressive strength as a result these become usable for concreting.
The S-6 sand (fineness modulus of 2.68) gives the compressive strength lower than the S-7 sand (fineness modulus of 1.94) due to the high percentage of calcium (81.8%) and low percentage of silica (6.7%). In case of S-5 sand, the effect is not pronounced as it has 29% of silica content.

The optimized sands show significant improvement of 8% to 39% in concrete strength.

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