The effect of silica fume inclusion on the properties of recycled concrete aggregate-containing concrete

P Akpinar1*, H M E Al Attar2
1Near East University, Civil Engineering Department, Lefkosa, N. Cyprus, Mersin 10, Turkey
2ACTED N.G.O. Ankawa, Erbil, KR-Iraq

*Email pinar.akpinar@neu.edu.tr

Abstract. Protecting the environment against the hazards of construction and demolishing (C&D) wastes is crucial. Elimination of C&D wastes by using them as recycled concrete aggregates (RCA) within the manufacture of new concretes is a promising solution for this problem. Since RCA coming from demolished structures have poor qualities, overall performance of new concrete should be monitored carefully. Without achieving a satisfactory strength performance, manufacturing concretes with RCA could not be widely accepted in construction sector. This study investigates the effects of silica fume, which is an effective pozzolanic material, on the properties of concrete mixtures made with 50% RCA as a replacement to quarried aggregates. RCA used was obtained from a 25-years old public building in Nicosia that was structurally failed and demolished. Results obtained indicated a 12.3% water demand increase for obtaining the targeted slump when SF was added in fresh concrete. The increase in compressive strength of concrete with SF in 28 days was 1.5%, where this increase was recorded as 8.1% at 90 days, yielding more than 65MPa strength. Also, addition of SF was observed to improve flexural strength of concrete samples up to a 4.3% at the age of 28 days, enabling the manufacture concrete mixtures apt for structural use.

1. Introduction
The increase in the world population and in the demand for construction activities lead to two major environmental problems. This increased demand in construction activities may lead to the depletion of natural resources for quarried aggregates, which are known to fill approximately the 75% of concrete volume. Secondly, the resultant construction and demolishing wastes that are majorly disposed as landfills, pose a threat for the nature. Construction and demolishing wastes disposed as landfills end up occupying agricultural lands with a considerable amount of non-biodegradable wastes, affecting the soil quality and making the land unsuitable for agriculture purposes. Moreover, leachate from construction and demolishing wastes are known to negatively ground water quality as well refs here.

Re-using demolished concrete wastes in the form of recycled concrete aggregates (RCA) in the manufacture of new concretes is considered as a potentially effective solution for both of the depletion of natural aggregates and landfill disposal-related problems. A recycled concrete aggregate particle is obtained by crushing the old demolished concrete elements to different sizes. Such a RCA particle consists of an original old natural aggregate with old mortar (from the demolished concrete) surrounding it. However, it is known that the porous and permeable nature of the old and damaged mortar in RCA may yield a lower quality for the new concrete that it is added to refs here. The use of RCA as a
replacement of natural aggregates in concrete manufacture for sustainable development of construction activities could only become widespread if the strength and the quality of new concrete produced with RCA is within acceptable ranges. The results of the previous studies showed that by carrying out an attentive mix design and by correct selection of concrete constituent materials and their quantities, the compressive strength of the concrete mixes could be improved greatly [1, 2]. Addition of silica fume into concrete has been reported to enhance different quality aspects of concrete as well [3, 4].

The aim of this study is to evaluate the effects of silica fume addition on the fresh and hardened concrete which is made with inclusion of recycled concrete aggregates obtained from a 25 years old reinforced concrete structure that had performance failure and hence demolished. The details on the experimental procedures and the results obtained are presented in below sections.

2. Materials and Methods

CEM II/B-S 42.5 N type of cement containing approximately 25% blast-furnace slag that conforms EN 197-1 (2011) [5] has been used in this study for the manufacture of concrete mixes. A constant cement content of 310 kg/m³ was used in the mixes, in which the cement: fine aggregates: coarse aggregates contents’ ratio employed was equivalent to 1: 3.01: 2.85. In the case of silica fume (SF) addition, the content of SF was set to 10 % of the cement by weight. The chemical composition of the used SF is as shown in Table 1 below.

Table 1. Chemical composition of silica fume used in this study

| Chemical Composition | Compound | SO₃ | SiO₂ | CaO | Na₂O | MgO | Al₂O₃ | Fe₂O₃ | K₂O |
|----------------------|----------|-----|------|-----|------|-----|-------|-------|-----|
| Content (%)          | -        | 94.3 | 0.30 | 0.27 | 0.43 | 0.09 | 0.01  | 0.830 |

Slump class of S4 as described in related standards [6] was targeted for the concrete mixes and a constant (1.29% of cement weight) superplasticizer content was employed in the manufacture of all concrete mixes. The required water/cement ratio for the studied concrete mixes to have the targeted S4 slump was determined through trial batches.

The sizes of coarse aggregates used in this study were graded in two size groups as 5-12mm and 13-19mm for both natural origin and recycled aggregates, where only natural (i.e. quarried) sand having a size range of 0-4mm was used in all mixes. The use of fine recycled concrete aggregates as a replacement of sand was defined to be out of the scope of this study. The natural (quarried, virgin) aggregates used in this study were obtained from the active quarries of Besparmak (Pentadaktylos) Mountains, where the recycled concrete aggregates were acquired from the wastes of a 25-years old public school building located in Nicosia, North Cyprus. The building was demolished by local authorities after a series of investigations that yielded the result that the building was experiencing structural failure, since its compressive strength was observed to be reduced to 12MPa. Figure 1 a and b shown the source building of the recycled concrete aggregates used in this study before and after being demolished. Once the building was demolished, the concrete parts freed from reinforcing steels and other contaminations such as broken bricks and glasses, were brought to laboratory and crushed down to desired sizes in order to replace natural aggregates in concrete manufacture. Prior to their use in the manufacture of new concrete mixes, detailed experimental studies were carried out on the specific gravity, density, absorption capacity and abrasion resistance of RCA used in this study. As a result of these tests, it was observed that the density, specific gravity and the abrasion resistance of RCA was lower than the natural aggregates, where the absorption capacity of RCA was found to be higher than natural aggregates used in this study. Information on the followed test procedures and the analysis of obtained results have been reported and discussed in detail in a previous work [7].
Three concrete mixes were designed in order to verify the influence of SF addition to the fresh and hardened properties of RCA-containing concrete. Mix 1 shown in Table 2 was casted for control purposes and it contained only natural aggregates (NA) and no RCA or no SF contents. Mix 2 was prepared by replacing 50% of the coarse natural aggregates with RCA but with no SF addition; where, mix 3 was prepared similar to mix 2 with the only difference of 10% (by mass of cement) silica fume addition.

| Concrete Mix No: | Replacement of coarse-NA with coarse-RCA | Silica fume addition |
|------------------|-----------------------------------------|----------------------|
| Mix 1            | 0                                       | 0                    |
| Mix 2            | 50%                                     | 0                    |
| Mix 3            | 50%                                     | 10%*                 |

*by mass of cement.

Besides the workability (slump) tests that are done to determine the water demand of these three mixtures in order to yield S4 class slump, a total of 27 cube samples, having 15x15x15cm³ dimensions, were casted in order to verify the compressive strength evolution of these mixes in 7, 28 and 90 days, following the related European standard [8]. In addition to the compressive strength behavior determination, 18 unreinforced beam samples, having 15x15x60cm³ dimensions, were also casted to study the flexural strength behavior of these mixes at the ages of 7 and 28 days, following the procedure of the related European standard [9]. The results obtained on the studies carried out on the fresh and hardened states of the employed three concrete mixes are presented in below sections.

3. Results and discussions

3.1. Effect of silica fume on workability characteristics of RCA-containing concrete

The workability characteristics of concrete mixes having a constant superplasticizer content that contain no RCA and no SF (mix 1), 50% RCA replacement (mix 2) and 50% RCA replacement together with SF addition (mix 3) have been studied in order to verify their water demand to maintain an S4 slump. After testing some trial batches, the final results regarding the water demands of these three mixes that yielded 18mm slump (i.e. within S4 class) have been reported in Table 3.
Table 3. Water/cement ratio for each mix needed for acquiring targeted slump

| Mix Content Summary* | Water/Cement Ratio | Slump (cm) |
|----------------------|--------------------|------------|
| Mix 1 0%RCA (100%NA) | 0.53               | 18         |
| Mix 2 50% RCA        | 0.57               | 18         |
| Mix 3 50% RCA & SF   | 0.64               | 18         |

*Where; NA: natural aggregates; RCA: recycled concrete aggregates; SF: Silica fume

Results obtained show that replacement of 50% of natural aggregates with RCA yielded a 7.5% increase in w/c needed for maintaining the defined slump value. This finding is expected to be due to the water absorption of adhered old mortar in RCA with a porous nature. Similar results have also been reported in the previous studies in the related literature (ref). When 10% (by mass of cement) silica fume was added to RCA-containing concrete mixture, an additional w/c increase of 12.3% was observed to be required in order to maintain the defined slump. Due to its fine particle character SF is known to yield a water demand increase in concrete (ref); however, addition of increased quantities of water is generally tried to be avoided in concrete mixes due to its expected decreasing effects on final strength of hardened concrete [10].

3.2. Effect of silica fume on compressive strength evolution of RCA-containing concrete

The average compressive strength values obtained for the ages of 7, 28 and 90 days for all mixes and their corresponding standard deviation values are presented in Table 4. Figure 2 illustrates the evolution of the compressive strength of studied mixes throughout 90 days. When the results shown in Table 4 and Figure 2 are considered, it can be observed that mix 1 which has no recycled concrete addition yielded the highest compressive strength values at every testing age. Replacing 50% of natural aggregates in mix1 with recycled concrete aggregates as in the case of mix 2, has been observed to yield a drop in the compressive strength performance of concrete at each age. This drop in strength (compared to mix1) is observed to be 12.9%, 23.7% and 17.2% at the ages of 7, 28 and 90 days, respectively. Poor quality of adhered old mortar in the RCA has been reported in the previous studies in the literature to cause a lower strength performance for the new concrete that it is added to [11-13].

Table 4. Average compressive strength and standard deviation values for all concrete mixes

| Mix Content Summary* | 7 days | 28 days | 90 days |
|----------------------|--------|---------|---------|
|                      | Strength (MPa) | Std. Dev. | Strength (MPa) | Std. Dev. | Strength (MPa) | Std. Dev. |
| Mix 1 0%RCA (100%NA) | 52.20  | 1.68    | 64.77   | 1.50    | 73.10   | 4.53      |
| Mix 2 50% RCA        | 45.47  | 1.72    | 49.40   | 4.73    | 60.53   | 2.15      |
| Mix 3 50% RCA & SF   | 48.97  | 0.64    | 50.13   | 0.31    | 65.43   | 0.85      |

*NA: natural aggregates; RCA: recycled concrete aggregates; SF: Silica fume

The results shown in Table 4 and Figure 2 also indicate that the addition of silica fume to RCA-containing concrete, as in the case of mix3, leads to higher strength values of compressive strength compared to the strength values yielded by mix 2 at every testing age. The increase in strength of RCA-containing concrete with the addition of SF compared to mix 2 is recorded to be 7.7%, 1.5% and 8.1% for the ages of 7, 28 and 90 days respectively.
It was observed that the increase in compressive strength acquired with 10% silica fume addition was not sufficient to compensate the decrease in strength yielded by replacement of natural aggregates by recycled concrete aggregates. Further experimental studies should be carried out on concrete mixes with increased silica fume contents in order to provide more insights on the effects of increased percentages of SF on the RCA-containing mixes.

3.3. Effect of silica fume on flexural strength evolution of RCA-containing concrete

Flexural strength evolution of employed three mixes was determined by testing three unreinforced beam samples of each mix at 7 and 28 days. The average flexural strength values, as well as the standard deviation values for each mix at every age are reported in Table 5. Figure 3 illustrates the evolution of flexural strength of the employed mixes within 28 days.

Table 5. Average flexural strength and standard deviation values for concrete mixes used

| Mix Content Summary* | 7-days | 28-days |
|----------------------|--------|---------|
|                      | Strength (MPa) | Std. Dev. | Strength (MPa) | Std. Dev. |
| Mix 1 0%RCA (100%NA) | 7.82    | 0.47    | 9.12    | 0.59    |
| Mix 3 50%RCA         | 4.91    | 0.16    | 6.34    | 0.19    |
| Mix 7 50%RCA &SF     | 5.10    | 0.38    | 6.61    | 0.44    |

* NA: natural aggregates; RCA: recycled concrete aggregates; SF: Silica fume

The results presented in Table 5 and Figure 3 show that flexural strength decrease of 37.2% and 30.5% were observed at the ages of 7 and 28 days respectively, when 50% of the natural aggregates were replaced with recycled concrete aggregates (i.e. the case of mix 2). Other researchers also report parallel findings in their works regarding the reduced flexural strength behavior of concretes made with RCA inclusion [14].
In the case of mix 3, the addition of SF was observed only a slight increase in the flexural strength; that was recorded as 3.9% and 4.3% at the ages of 7 and 28 days, with the comparison of values obtained by mix 2 and mix 3. The increase in the flexural strength of RCA-containing concrete with the addition of SF was observed to be of lower percentages, compared to the increase in compressive strength with SF addition. These obtained results indicate that the effect of SF addition to the flexural strength of RCA-containing concrete is less than its effects on compressive strength performance.

The cases of increased SF contents addition with the use of varying % RCA replacements in concrete mixtures should be further investigated with detailed experimental studies, in order to provide a broader view on the influence of silica fume on the performance of RCA-containing concretes in hardened state.

4. Conclusive remarks
Recycled concrete aggregates obtained from a 25-years old structurally failed reinforced concrete building were used to replace 50% of the natural aggregates in the manufacture of new concrete mixes. As it is known that the use RCA reduces performance of new concrete manufactures, 10% silica fume was added to the concrete mix and the effect of silica fume on the fresh and hardened characteristics of the RCA-containing concrete was studied systematically. The conclusive remarks acquired from this experimental study are as the following:

- The addition of silica fume to RCA-containing concrete caused a water demand increase of 12.3% in order to maintain the defined concrete slump value. This additional water included in concrete is expected to cause potentially adverse effects on the ultimate strength of concrete to an extent that should be further investigated.
- The addition of silica fume to RCA-containing concrete was observed to positively affect the compressive strength. An increase of 8.1% in the compressive strength of RCA-containing concrete was observed at the age of 90 days when 10% SF was added to the mix. However, this quantity was observed to be not sufficient to compensate the decrease in strength experienced due to 50% RCA replacement in concrete.
- Including 10% SF to RCA-containing concrete has also observed to be also yielding a slight improvement in the flexural strength of concrete. The percentage increase recorded for flexural strength with the addition of SF is lower than the percentage increase recorded for compressive strength of RCA-containing concrete.
Further experimental studies should be carried out with varying SF quantities added to concrete having different RCA contents, in order to provide more insight on the resultant influence of SF addition in a more detailed way for both fresh and hardened concrete.

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