Treatments for the Improvement of Recycled Aggregate

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Abstract: The microstructure of recycled aggregate prepared from the crushing of old concrete was studied. It was found that the recycled aggregate is covered with loose particles that may prevent good bonding between the new cement matrix and the recycled aggregate. The old cement paste that remained on the natural aggregate was porous and cracked, leading to weak mechanical properties of the recycled aggregate. Treatment of the recycled aggregate by impregnation of silica fume solution and by ultrasonic cleaning was studied with the objective of overcoming the above-mentioned limitations. An increase of ~30 and ~15% in the compressive strength at ages 7 and 28 days was observed after the silica fume treatment. Ultrasonic treatment led to an improvement of ~7%.

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Introduction

Crushed concrete is available nowadays in large quantities, which results from the demolition of old structures and waste concrete from new structures. A report presented in 1999 to the European Commission estimated the amount of nonrecycled construction waste to be 130 million t/year. The area required for landfilling this amount of waste is equivalent to the accumulation of waste, 1.3 m high, over the entire central Paris area (Symonds 1999). It appears that recycling construction waste is vital both in order to reduce the amount of open land needed for landfilling and to reduce depletion of raw materials.

Many attempts to develop high-grade uses of construction waste, i.e., as aggregate for the manufacturing of new concrete, are reported in the literature (Topcu and Guncan 1995; Collins 1996; Tavakoli and Soroushian 1996). A decrease in the compressive strength was generally observed in all concretes in which the natural coarse aggregate was replaced with recycled aggregate prepared by the crushing of old concrete. The mechanical properties of the concrete decreased with the increase in the proportion of aggregate replaced (Topcu and Guncan 1995; van Acker 1996; Teranishi et al. 1998). Incorporation of fine aggregate from crushed concrete in the production of new concrete leads to an even greater decrease in the mechanical properties (Hansen and Marga 1988). RILEM Technical Committee 121-DRG (1994) recommended that only 20% of the natural aggregate can be replaced with recycled coarse aggregate in the preparation of new concrete of all strength classes, and limited the concrete classes when 100% recycled construction waste is used.

Several methods to improve the properties of new concrete made from recycled aggregate were reported in the literature. Sri Ravindrarajah and Tam (1988) improved the properties of new concrete by altering the water/cement ratio, adding pozzolans, and blending recycled and natural aggregates. These techniques, however, refer to general concrete technology and not to the improvement of the recycled aggregate itself. Montgomery (1998) treated the aggregate with a ball mill in order to remove old cement paste from natural stone. He found that the cleaner the aggregate was, the stronger was the concrete. Winkler and Mueller (1998) and Montgomery (1998) milled recycled fines and used them as a cement replacement. A reduction of 17% in the compressive strength of the concrete, at a replacement ratio of 33%, is reported by Montgomery.

In the present study, the microstructure of recycled aggregate (hereinafter denoted as R-aggregate) made from old concrete of three strength classes was studied, and several methods to improve the properties of the aggregate were evaluated.

Experimental Program

The experimental program included the following steps:

1. Preparation of concrete, at three levels of strength, to serve as base concretes for further investigation of the properties of the crushed material;
2. Crushing of the base concretes, after testing their compressive strength at 28 days;
3. Analysis of the properties of the crushed concrete (R-aggregates);
4. Treatments to improve the R-aggregates properties (ultrasonic cleaning and silica fume impregnation); and
5. Preparation of new concretes using the R-aggregates, after treatment and testing of their properties.

Base Concrete and Recycled Aggregates

The base concretes for the treatments were produced first. Three types of concrete were prepared using three water/cement ratios (0.77, 0.53, and 0.35), representing three levels of strength (low, medium, and high, denoted as concrete A, B, and C, respectively). The mix compositions of the base concretes are presented in Table 1. Approximately 25 cubes, $100 \times 100 \times 100$ mm^3, were prepared and stored in a moist room for 7 days, followed by an additional period of 21 days in the laboratory air. At age 28 days,

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Table 1. Mix Composition and Properties of the Base Concretes (kg/m^3)

Ingredient	Concrete A	Concrete B	Concrete C
9.5–19 mm aggregate	905	905	905
2.36–9.5 mm aggregate	455	455	455
Fine aggregate	600	485	315
Water	200	200	200
Cement	260	380	570
Water/cement ratio	0.77	0.53	0.35
Compressive strength at 28 days	27.4 MPa	52.5 MPa	66.8 MPa

Table 2. Properties of Recycled Aggregates

Property	Aggregate RA	Aggregate RB	Aggregate RC
Bulk specific gravity	2.48	2.41	2.46
Bulk density (kg/m^3)	1,356	1,353	1,348
Absorption (%)[a]	5.1	5.5	5.3
Uptake of SF solution (%)[b]	9.0	8.4	7.6

[a]Dry to saturated surface dry (SSD).

[b]Dry to saturated surface wet.

the base concretes were tested for compressive strength. Results of these tests are presented in Table 1 as well. After the tests, the fractured concretes were crushed using a mini jaw crusher with a maximum opening of 20 mm. Sieve analyses of the crushed concretes are presented in Fig. 1, and other properties of the recycled aggregates (absorption, bulk density, and unit weight) are presented in Table 2. Despite the differences between the compressive strengths of the concretes, grain size distribution and other properties were quite similar, in accordance with results published in a previous study (Katz 2003).

Microstructure of the Crushed Concrete

A study of the surface structure of the crushed concrete particles, using a scanning electron microscope (SEM), showed that the surface is covered with a significant amount of crumbs (Fig. 2). The crumbs range in size from a few microns to several hundreds microns, and they are loosely connected to the bulk aggregate. These crumbs are most likely the result of the crushing of the old concrete, and in particular, the old cement paste (Winkler and Mueller 1998).

The aggregate was cleaned in an ultrasonic bath in order to remove all loose particles and to expose the surface of the bulk aggregate (Fig. 3). A virgin aggregate surface from the old concrete is seen [upper right corner of Fig. 3(a) and lower left corner of Fig. 3(b)] together with the old cement matrix that surrounds it. The cracks and damage to the cement matrix, seen in the image, are the result of stress induced during the crushing process. Significant differences are seen between the aggregates from concrete A and concrete C [Figs. 3(a and b), respectively], as follows: The old cement matrix of concrete A is more porous and damaged than that of concrete C, a result of the latter's superior properties.

Two effects seem to have a detrimental effect on the quality of the recycled aggregates (apart from the water/cement ratio of the old cement matrix). These are (1) coating of aggregates with loose particles, which damages the bond between the new cement matrix and the recycled aggregate and (2) cracking of the old cement matrix, which decreases the mechanical strength of the recycled aggregate.

Treatments to Improve the R-Aggregate

Two methods were proposed to improve the quality of the recycled aggregates:

1. Impregnation with a solution of silica fume that is intended to add a thin layer of silica fume particles over the surface of the recycled aggregate. The silica fume is expected to react with calcium hydroxide from the hydration of the cement to form a dense layer covering the surface of the aggregate, which, in turn, will increase its strength.
2. Ultrasonic cleaning of the recycled aggregate in order to remove the loose particles and improve the bond between the new cement paste and the recycled aggregate.

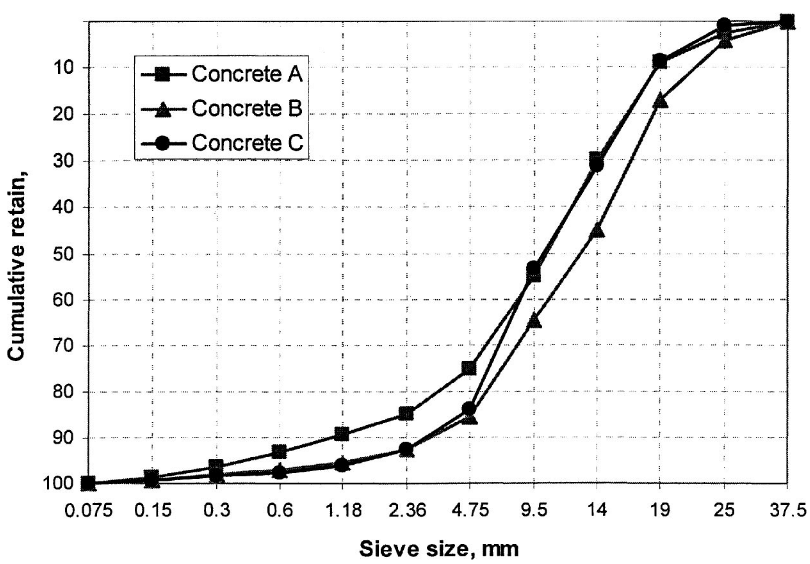


Fig. 1. Sieve analysis of crushed base concrete

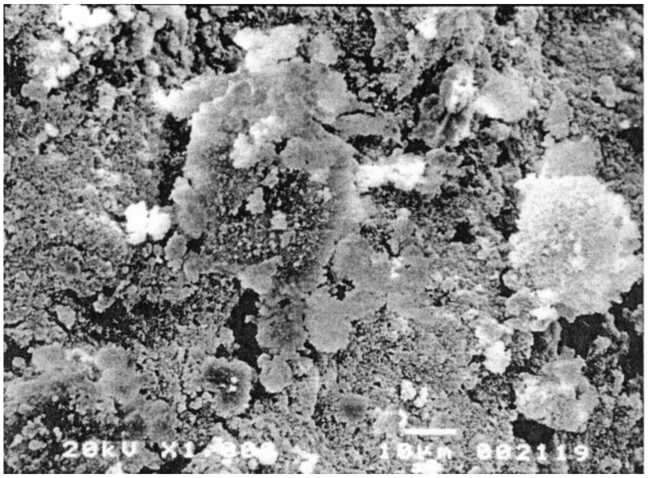


Fig. 2. SEM micrograph of the surface of untreated recycled aggregate covered with loose crumbs (concrete C)

Silica Fume Impregnation

A solution of 10 L of water and 1 kg raw silica fume (noncondensed, see properties in Table 3) was prepared by mixing small batches of solution in a Hobart mixer, super plasticizer (1% weight of silica fume) was added to ensure proper dispersion of the silica fume particles. The dispersion in water of commercially available condensed silica fume was found to be insufficient, thus raw silica fume was used in this study.

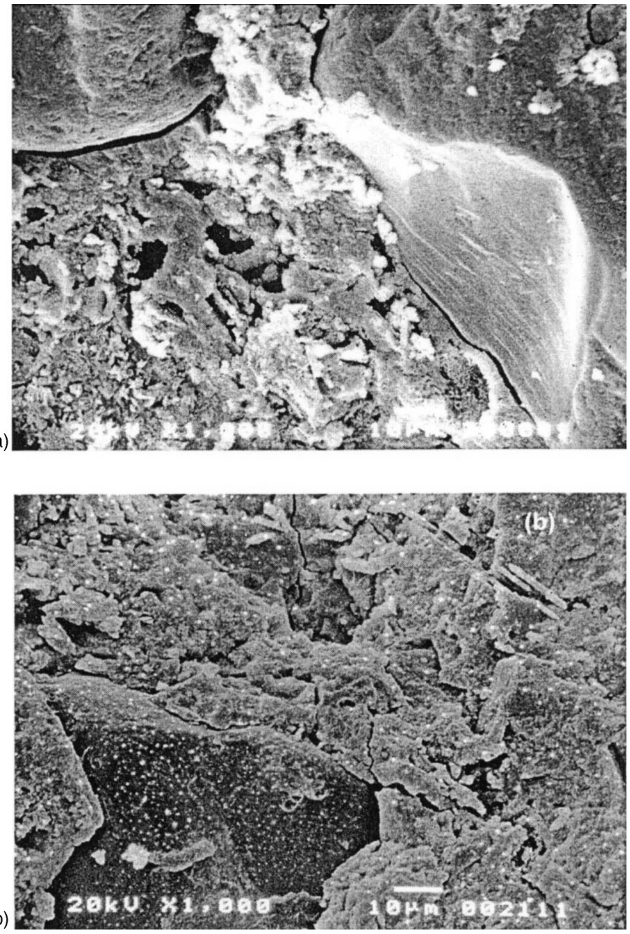
The R-aggregate was dried in an oven for 48 h, cooled back to room temperature, and soaked in the silica fume solution for 24 h. Weight measurements were taken before and after the silica fume treatment. The saturated aggregate was then dried again in the oven to ensure proper penetration of the silica fume particles into the surface of the aggregate and weighted again after drying. No measurable amount of silica fume was detected by weight gain of the dry aggregate before and after the silica fume treatment. However, the amount of silica fume impregnated into the surface of the R-aggregate can be estimated at 0.5–0.8% of the aggregate weight based on the weight gain after it was taken out of the silica fume (SF) solution and considering an approximate efficiency rate of 2/3 for the process (Table 2). Fig. 4 presents the scanning electron microscope (SEM) images of the recycled aggregate surface (from concrete C) after the silica fume impregnation. After impregnation, the surface is covered with a layer of silica fume particles and some crumbs are still seen, though in smaller quantities. Natural aggregate was also treated with silica fume to compare the effect of treatment on a relatively nonporous aggregate (~1% absorption) with a solid structure.

Ultrasonic Cleaning

The crushed concrete was cleaned in an ultrasonic (US) bath to remove the crumbs observed on the surface of the untreated aggregate (Fig. 2). The aggregate was immersed in the US bath with a large amount of water and was treated for 10 min, after which the water was replaced with clean water and the aggregate was cleaned for an additional 10 min. This action was repeated several times until clear water was obtained. The SEM image of the clean surface is presented in Fig. 3.

During the cleaning process it was noticed that recycled aggregate from low grade concrete required more cleaning cycles until clear water was obtained than the higher grade concrete. The cement matrix of lower grade concrete tends to break first when the concrete is crushed, possibly producing larger quantities of fine particles than high grade concrete, as was noticed qualitatively above.

(a)



(b)

Fig. 3. SEM micrograph of the surface of recycled aggregate cleaned in an ultrasonic bath to remove loose crumbs (top: concrete A and bottom: concrete C)

Preparation and Properties of New Concrete

Preparation of New Concrete

New concrete was prepared from the coarse fraction of the recycled aggregate (4.75–19 mm) with the addition of natural sand. Two groups of specimens were prepared for each treatment: concrete with treated aggregate and reference concrete with untreated aggregate. In addition, concrete containing natural aggregate (silica fume treated and untreated) was prepared, denoted as "Nat." Table 4 presents the mix composition of the new concretes. It should be noted, when comparing the results, that the cement used for the production of the new concretes after aggregate treat-

Table 3. Properties of Raw Silica Fume

Loss on ignition	SiO_2 content	Specific surface area (BET)
3.4%	90.5%	25.8 (m^2/g)

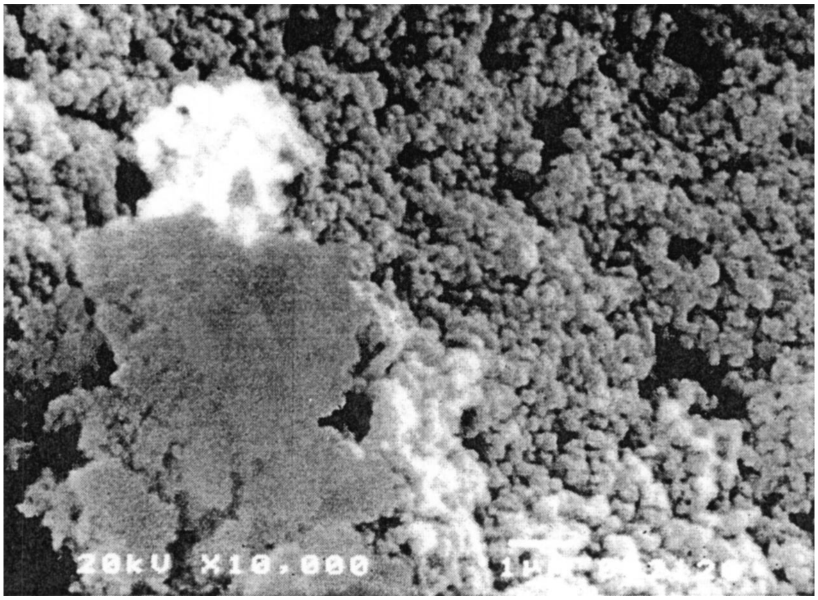


Fig. 4. SEM micrograph of the surface of recycled aggregate after silica fume impregnation (concrete C)

ment was taken from a different batch, thus the strength results of the new concrete cannot be compared with data from the base concretes.

During the mixing of the new concretes, it was noticed that the workability of the concrete made with silica fume treated aggregate was somewhat better than that of the other concretes. Unfortunately, the small batch volumes did not enable slump measurements to provide accurate workability values. It is possible, therefore, that silica fume particles on the surface of the R-aggregate prevented the penetration of some of the water into the R-aggregate pores, leaving more free water in the mix, which in turn may increase the water/cement ratio.

Compressive Strength of New Concrete

Results of compressive strength tests at 7 and 28 days are presented in Table 5 and Figs. 5 and 6. At least three cubes $100 \times 100 \times 100\ mm^3$ were tested at each age. The SF treatment seems to improve significantly the strength of the new R-aggregate concrete at both 7 and 28 days. The improvement at age 7 days ranged from 23 to 33%, and at 28 days reached a lesser extent of 13–16%. A limited number of specimens made with R-aggregates from base concretes B and C (RB and RC) also tested at 90 days were found to exhibit values similar to those found at 28 days. It seems that the SF treatment has a better effect in early age than later on by increasing the density of the cement matrix near the recycled aggregate and improving the composite effect of the material when the new cement matrix is relatively weak. At a later age, the new cement matrix becomes stronger than the recycled aggregates and a lesser improvement in strength is observed.

A negative effect was observed in the concrete prepared from natural aggregate. The compressive strength of the untreated concrete containing natural aggregate was greater than that of the concrete prepared with R-aggregate. However, silica fume treatment led to a decrease in compressive strength; the opposite effect from that seen with the recycled aggregate.

It can be seen from Fig. 6 that the effect of ultrasonic cleaning is smaller than that of SF impregnation. US cleaning yielded a 15% improvement for concrete made with R-aggregate from base concrete B (RB), but only a 3% improvement for R-aggregate RC at age 7 days. At age 28 days the improvement was only 7% for both types of R-aggregate.

Discussion

The results indicate an improvement in the properties of recycled aggregate after both treatments. The more effective treatment was SF impregnation and its effect was more significant at an early age.

It seems that silica fume improves the properties of new concrete made from recycled aggregate in two ways: (1) by improv-

Table 4. Mix Composition of New Concrete (kg/m^3)

Ingredient	SF treatment	US treatment
Aggregate 4.75–19 mm (recycled)	1,235	1,080
Fine aggregate	475	670
Water	195	190
Cement	365	333

Table 5. Compressive Strength of Treated Concrete

	7 days		28 days	
Mix type	Strength (MPa)	Change (%)	Strength (MPa)	Change (%)
SF-RA/(Ref)	34.4/(27.2)	+26	47.8/(42.3)	+13
SF-RB/(Ref)	33.5/(27.3)	+23	49.3/(42.8)	+15
SF-RC/(Ref)	37.6/(28.4)	+33	51.3/(44.3)	+16
SF-natural/(Ref)	24.2/(31.0)	−22	39.5/(45.7)	−13
US-RB/(Ref)	27.9/(24.2)	+15	41.2/(38.7)	+7
US-RC/(Ref)	24.4/(23.8)	+3	40.8/(38.2)	+7

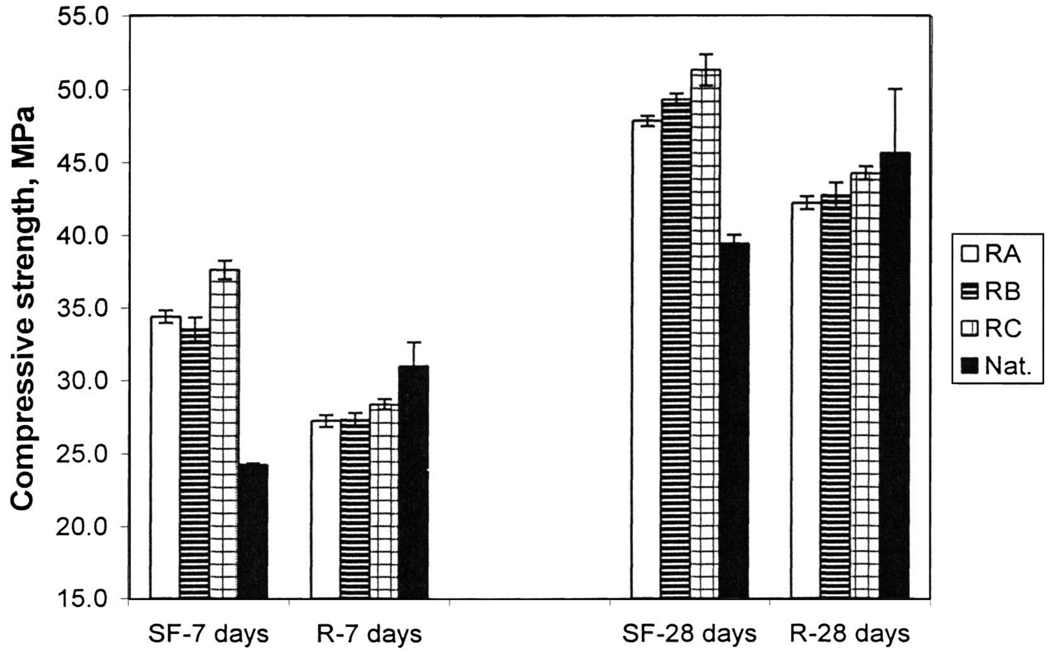


Fig. 5. Comparison between compressive strength of concrete made with SF treated and nontreated recycled aggregate

ing the interface between the R-aggregate and the new cement matrix; and (2) by strengthening the structure of the old paste that is still adhered to the R-aggregate, which has cracked during the crushing process.

Modification of the interfacial transition zone between the aggregates and the bulk matrix of concrete by using silica fume is a common technique applied nowadays to improve concrete properties (Lagerblad 1999). Silica fume acts as a microfiller, filling the transition zone between the aggregate surface and the bulk cement matrix, followed by a pozzolanic reaction at the same place (Goldman and Bentur 1993). When porous aggregate is involved, as in lightweight aggregates or the R-aggregate used in this study, the interfacial transition zone extends from a certain distance below the surface of the aggregate out to the bulk cement matrix (Katz et al. 1999). Impregnation of the R-aggregate with a silica fume solution introduces SF particles into the cracked and loose layer of this aggregate. During concrete hardening, this layer improves the interfacial transition zone, as noted above, through the filler effect. In addition, further pozzolanic reaction between the silica fume and the portlandite strengthen the weak structure of the R-aggregate to form an improved zone, which extends from the natural aggregate through the residues of the old cement paste into the new cement matrix. The stronger effect of the silica fume treatment at an early age indicates that the filler effect of the silica fume is more dominant in improving the R-aggregate than the pozzolanic reaction, which is known to develop more slowly.

It should be noted that the amount of silica fume in the new concrete is estimated at ~2.5% of the cement in the new concrete, based on the weight gain after absorption of the silica fume

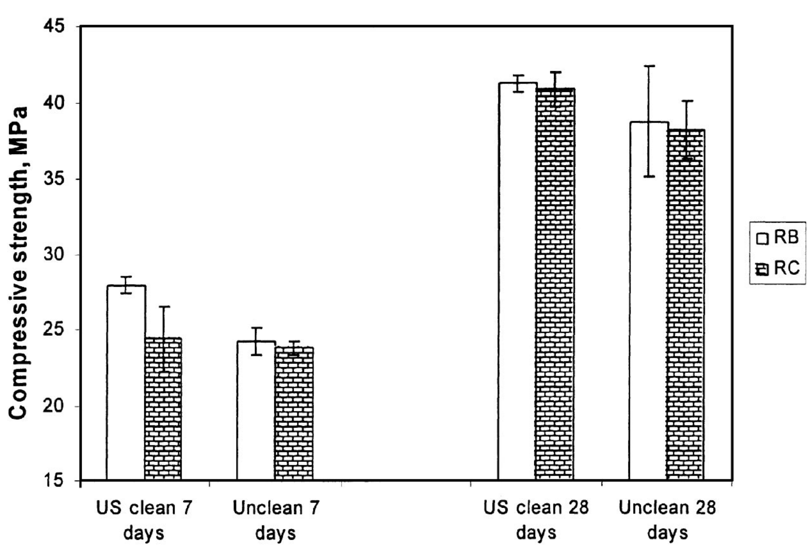


Fig. 6. Comparison between compressive strength of concretes made with US treated and nontreated recycled aggregate

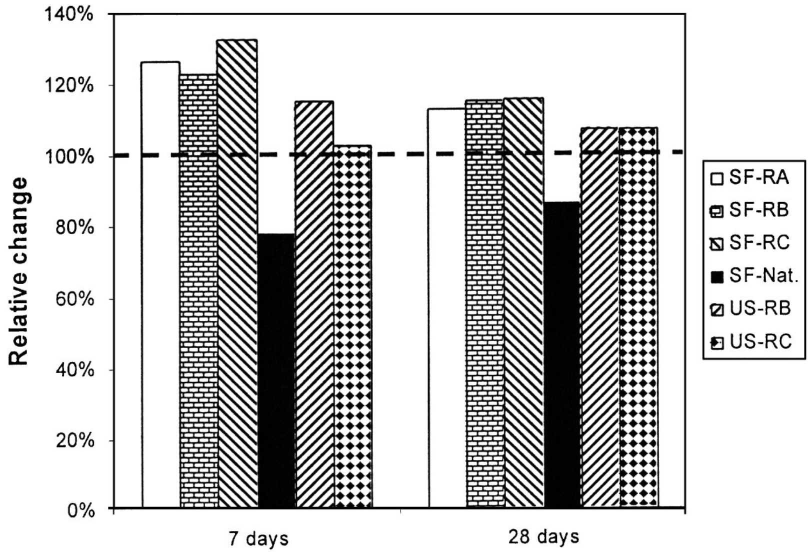


Fig. 7. Effect of treatment on compressive strength of treated versus untreated aggregate

solution (this estimate is somewhat higher than the actual amount that penetrated the aggregate, since some silica fume was left in the pan after drying the R-aggregate). This amount of silica fume is very small and is not known to have any significant effect on the properties of ordinary concrete.

The use of aggregate that is inferior to the cement matrix (such as lightweight aggregate or recycled aggregate) generally reduces the mechanical properties of the concrete, as seen by the comparison of the strengths of untreated natural- and R-aggregate concrete. At an early age, improvement of the R-aggregate leads to a significant improvement of 23–33% in the compressive strength of the concrete, since the properties of the modified R-aggregate and the new cement matrix differ only slightly (Fig. 7). A stronger aggregate (aggregate RC) produces stronger concrete. At a later age, after strengthening of the new cement matrix, the difference between the properties of the R-aggregate and the cement matrix increases and the effect of aggregate treatment is reduced to only 15% for all sources of aggregates.

On a solid and relatively impervious aggregate surface, such as natural aggregate, the silica fume creates a separating layer, which impairs the bond between the cement matrix and the aggregate, leading to a decrease in the properties of the concrete (Fig. 7). It appears that the degree of roughness of the aggregate surface and the size and texture of the pores at the surface, have a significant effect on the efficiency of the treatment. Thus a positive effect is observed on a cracked, porous, and damaged surface as opposed to the negative effect observed on a solid and impervious surface.

Thorough removal of the loose particles from the surface of the R-aggregate improved the contact between the new cement matrix and the aggregate, but only to a low level of a few percent (Fig. 7). It seems that the broken structure of the old cement paste still adhered to the natural aggregate controls the properties of the R-aggregate and of the new concrete made from it.

Summary and Conclusions

Scanning electron microscopy of recycled aggregates derived from the crushing of old concrete showed extensive cracking of the old cement paste that remained adhered to the natural aggregate. In addition, contamination of the surface of the crushed concrete by small particles that were loosely connected to the aggregate was observed.

Two treatments were evaluated, with the purpose of improving the surface properties of the R-aggregate: (1) impregnation of the recycled aggregate with a 10% by weight silica fume solution; and (2) ultrasonic cleaning of the R-aggregate to remove loose particles from its surface.

The silica fume treatment resulted in an increase of 23–33% and ~15% in the compressive strength at ages 7 and 28 days, respectively. Ultrasonic treatment yielded a moderate increase of ~7%, with no clear difference between early and late ages.

It appears that silica fume impregnation improves both the interfacial transition zone between the R-aggregate and the new cement matrix, and the mechanical properties of the R-aggregate. As a result, the early strength of the new concrete increases significantly when the disparity between the properties of the R-aggregate and the new cement matrix is relatively small and the filler effect of the silica fume is dominant. At a later age, after the cement matrix has strengthened, these effects are weaker, leading to a lesser influence on the strength. Cracking of the old cement matrix seems to have a strong influence on the properties of the R-aggregate.

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