Fresh and hardened properties of self-compacting concrete incorporating PVA-treated recycled aggregate

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Abstract. In this paper, an experimental study was undertaken to improve the fresh and hardened characteristics of normal (NS) and high strength (HS) self-compacting concrete (SCC) mixes made with recycled aggregate (RA). An easy-to-perform treatment method was proposed to enhance RA properties: in this method, RA was first subjected to partial removal of adhered mortar, then treated with polyvinyl alcohol (PVA) solution for 24 hours. A series of SCC mixes, varying in w/c ratio and coarse aggregate type, including natural aggregate (NA), recycled aggregate (RA), and treated recycled aggregate (TRA), were prepared for this investigation. All mixes were investigated in their fresh state using slump flow and J-ring tests, and in their hardened state using compressive strength, splitting tensile strength, and modulus of elasticity tests. The results demonstrated that the proposed treatment method is reliable in terms of improving the properties of RA. With the exception of the passing-ability test for RA concrete mixes, all tested SCC mixes met the self-compactibility and segregation resistance criteria. Additionally, the investigated hardened properties of TRA self-compacting concrete mixes were improved significantly by using the proposed treatment method compared with those of untreated RA concrete mixes.

Keywords: recycled aggregate, polyvinyl alcohol, SCC, compressive strength, slump flow, J-ring.

1. Introduction

Concrete is one of the most plentiful man-made composite materials globally, and steadily reached its popularity since its inception. As it is the most consumed construction material for buildings and infrastructures, the demand for concrete is very high at present and it is projected to have similar significance in the future. Nevertheless, conventional concrete cannot be considered an environmentally friendly construction material, based on the perspective that it depletes natural resources, requires high energy consumption, and generates construction waste for disposal [1]. Consequently, the necessity for greater utilisation of renewable and recyclable resources in concrete industries is of prime importance. A reasonable option for this is the use of recycled aggregate (RA) instead of normal aggregate (NA).

Recycled aggregate (RA) is a material abundantly sourced from the demolition of reinforced concrete buildings, bridges, and pavements. Over the past two decades, attempts to utilise RA in concrete industries have been developed, and a large number of studies have been conducted. In terms of its mechanical performance, RA concrete is generally found to be applicable for use as structural concrete [2–5]. However, the influence of type and substitution
percentages of RA on concrete’s mechanical properties, and its consequent influence on durability performance, remain under inspection, as inconsistent results have been reported [6]. The microstructure of RA concrete cannot be compared with that of conventional concrete, as the former has a different microstructure due to containing two kinds of interfacial transition zones (ITZ); this is because, in addition to old ITZ between adhered mortar and aggregate, it contains new ITZ between the old RA and new cement mortar [2]. As the strength of a concrete mix depends significantly on its mortar-aggregate bond [7], the presence of these ITZs (through which failure occurs) makes RA concrete weaker than NA concrete [8,9].

A significant amount of research work has been done, and this suggests that the compressive strength of concrete produced with 100% RA is decreased by up to 20% as compared with that of NA concrete [10–13]. Furthermore, the splitting tensile strength of concrete made with 100% RA drops up to 30% [14,15]. In terms of modulus of elasticity, concrete containing 100% RA tends to see a reduction ranging from 15 to 22% compared with that of NA concrete [10,15], depending on the qualities of the original concrete and the properties of the RA used. However, a more noticeable reduction of about 40% was also observed in some cases [17,18].

To overcome the challenge of inferior properties, several studies on improving RA performance have been carried out to examine various process improvement techniques. Of these techniques, the one offering the most acceptable level of performance is removing the adhered old mortar from RA at such a level as to minimise its adverse influences [15]. This can be achieved by subjecting RA to mechanical grinding, chemical treatment, and heat treatment. Another technique that has been implemented to improve the quality of RA is adding various mineral admixtures. It has been concluded that addition of limestone filler and pozzolanic materials such as silica fume, metakaolin, fly ash, and ground granulated blast slag, plays an essential role in improving RA physical and mechanical properties [19,20]. An admixture of water reducer [21], steel fibre [22], and polymer emulsion [23, 24] can also be added to mitigate any inferior mechanical properties, allowing RA concrete strength to be made equal to that of NA concrete. Among the polymer emulsions, polyvinyl alcohol (PVA), up to a certain limit, has been found to have the most positive influence on concrete’s fresh and hardened properties [24].

According to the extensive research work seen in the literature, the focus has primarily been on producing conventional concrete (CC) rather than self-compacting concrete (SCC). Due to its low quantities of coarse aggregate, SCC may demonstrate inferior fracture cracking behaviours, which raises concerns among researchers, and this issue may be aggravated when RA is used in SCC mixes, as the concrete produced has additional interfacial transition zones (ITZs), resulting in more complicated microstructures than in NA concrete [2]. In this paper, the aim is to experimentally assess the feasibility of enhancing the fresh and hardened properties of self-compacting concrete mixes made with 100% treated recycled aggregate (TRA). For this purpose, RAs were first subjected to a simple treatment method to (1) reduce the amount of adhered mortar and (2) improve their properties via impregnation with an optimum concentration of polyvinyl alcohol (PVA) polymer solution. After completing the treatment process, several NS and HS self-compacting concrete mixes (incorporating RA and TRA as well as NA) were tested in the fresh state, using the flow and passing ability tests, and in the hardened state, using compressive strength, splitting tensile strength and modulus of elasticity tests.
2. Experimental program

2.1. Materials

In this experimental study, locally available type I Portland cement was used. Three types of coarse aggregates (with a maximum size of 20 mm) were used: natural aggregate (NA), recycled aggregate (RA), and treated recycled aggregate (TRA). The RA was prepared by crushing old concrete cube specimens available in the structural laboratory of the College of Engineering. Natural river sand of 4.75 mm size and a specific gravity of 2.61 was used as a fine aggregate, conforming to the requirements of Iraqi speciation (IQS) No. 45/1984. A crushed aggregate with a maximum size of 20 mm and 2.66 specific gravity was used. For the preparation of SCC mixes, limestone powder (<125 μm and specific gravity 2.52) was used. A superplasticizer, commercially known “Visocrete-5930”, which meets the requirement for superplasticizer given in ASTM C-494 types G was used throughout this study. Tap water was used for both mixing and curing the produced concrete mixes. The materials used in this research also included polyvinyl alcohol (PVA) polymer, which was used to treat RA particles. This was 88% hydrolysed with a molecular weight of approximately 14,000. The PVA was provided by the Advanced Technology and Industrial Company Limited.

2.2. Treatment of RA

During the crushing of old concrete specimens, significant quantities of adhered mortar remain attached to the RA surfaces, which may cause defective porous and weak layers to be formed, leading to high water absorption, high porosity, and low density, adversely affecting the properties of the resultant RA. This can be a severe problem in concrete structures influencing their strength and durability [21]. Thus, to improve the quality and to achieve adequate performance of RA, a reliable method of treatment is required to remove the weak old mortar and to enhance the remaining microstructure. This can be done by enhancing the bond strength between the original aggregates and the remaining cement matrix. In this study, a simple and low-cost treatment method was proposed to enhance RA properties that involved two steps: (1) removal of adhered loose mortar and (2) impregnation with PVA solution.

2.2.1. Removal of adhered mortar

In order to remove the loose and weak adhered mortar, the RA was placed in a concrete mixer and rotated. During this process, water was continually added until the trapped dust, smaller particles, and loose adhering mortar were removed. After completing this washing process, the RA was left to air-dry and then sieved using standard sieves for coarse aggregate in order to reject RA particles sized less than 5 mm to achieve the required size of 5 to 20 mm. The final RA product showed considerably better appearance (see Figure 1) and properties, as described in section 3.1.
2.2.2. Impregnation with PVA

The procedure of RA impregnation with PVA solution is summarised as follows.

1. PVA powder of 50g, 100g, 150g, and 200g were each added to and dissolved in 5 litres of boiled water for about 90 minutes to prepare PVA solution concentrations of 1%, 2%, 3%, and 4%, respectively.
2. After dissolving the PVA powder, the solutions were left to cool down at ambient temperature in the lab and kept in plastic containers.
3. The prepared RA (having been subjected to the mortar removal process) was then immersed in PVA solution for 24 h. This period of immersion was also proposed in [24].
4. The immersed RA was removed and air-dried in the lab before being subjected to the required tests.
5. An adequate amount of PVA solution was prepared and the above procedure was followed for each tested batch.

2.3. Mix proportioning

The experimental work was dedicated to producing relatively different normal and high strength self-compacting concrete mixes, with characteristic cube compressive strengths of 30 and 50 MPa, with corresponding water to cement (w/c) ratios of 0.57 and 0.35, respectively. In these mixes, different types of coarse aggregates (in saturated surface dried (SSD) condition) were used: natural, recycled, and treated recycled aggregates. The prepared SCC mixes were proportioned based on the rational mix design method proposed in [25]. These were designated NA, RA, TRA, NS, and HS for natural aggregate, recycled aggregate, treated recycled aggregate, normal compressive strength, and high compressive strength, respectively. The coarse aggregate of the control mixes (NA-NS and NA-HS) was natural coarse aggregate at a 0% RA replacement ratio. In the remaining mixes, NA was replaced either with 100% RA or 100% TRA. This replacement was volumetrically performed (according to the specific gravity of the aggregates used, as shown in Table 2) in order to keep the amount of fine materials (cement and limestone powder), water, and fine aggregates constant in each of the respective SCC mix groups. The constituent materials of all prepared mixes are presented in Table 1.
Table 1: Constituent materials of the tested SCC mixes, kg/m³

| Mix notation | Cement | Water | w/c | Superplasticiser | Limestone powder | Fine aggregate | Coarse aggregate |
|--------------|--------|-------|-----|------------------|-----------------|---------------|-----------------|
| NA-NS        | 350    | 199   | 0.57| 5.2              | 160             | 770           | 830             |
| RA-NS        | 400    | 199   | 0.57| 5.2              | 160             | 770           | 746             |
| TRA-NS       | 350    | 199   | 0.57| 5.2              | 160             | 770           | 746             |
| NA-HS        | 490    | 171.5 | 0.35| 7.8              | 105             | 750           | 750             |
| RA-HS        | 490    | 171.5 | 0.35| 7.8              | 105             | 750           | 750             |
| TRA-HS       | 490    | 171.5 | 0.35| 7.8              | 105             | 750           | 774             |

2.4. Concrete specimen casting and testing

Experimental work was carried out to investigate the fresh and hardened SCC mixes. The fresh mixes were thus subjected to slump flow and J–ring tests according to BS EN 206-9 [26] and EFNARC [27]. For each concrete mix, several 100*200 mm cylinders and 100*100*100 mm cubes were cast. The specimens were demoulded after 24 h and then cured in a water curing tank in a laboratory environment for 28 days. The average values for three specimens were determined for each mix. The compressive strength, splitting tensile strength, and modulus of elasticity were measured according to BS EN 12390-3 [28], BS EN 12390-6 [29], and BS 1881-121 [30], respectively.

3. Results and discussion

3.1. Properties of aggregates

The properties of the aggregates used are shown in Figure 2: Physical properties of treated RA...
Table 2: Properties of coarse aggregates.

| Property               | Natural aggregate | Treated RCA | Untreated RA |
|------------------------|-------------------|-------------|--------------|
| Specific gravity (SSD) | 2.66              | 2.42        | 2.39         |
| Water absorption (%)   | 1.6               | 2.2         | 5.9          |
| LA abrasion (%)        | 21.3              | 24.9        | 28.0         |

3.2. Fresh properties of concrete mixes

3.2.1 Flow-ability

As per EFNARC guidelines [27], the flow-ability of SCC mixes was evidenced by determining their $t_{50}$ and by using the slump flow test. The $t_{50}$ represents the time required for the fresh mix to reach a 50 cm diameter spread in a horizontal flow. Depending on the concrete application, EFNARC guidelines [27] classify the slump flow (SF) of SCC into three classes: SF1 (from 550 to 650 mm); SF2 (from 650 to 750 mm), and SF3 (from 750 to 850 mm). In this study, the produced SCC mixes complied with the SF2 class (which is the most popular class in concrete construction). For this to be achieved, the superplasticizer (SP) dosage was adjusted from 3.5 to 5.2 kg and 6.3 to 7.5 kg for normal and high strength mix grades, respectively. Within the chosen slump flow class (SF2), Table 3 shows that $t_{50}$ ranged from 1.3 to 2.1 s and 2.2 to 3.0 s for normal and high strength mix grades, respectively. The $t_{50}$ of fresh SCC containing RA was relatively higher than that of NA; however, $t_{50}$ was only slightly influenced when TRA was used instead of NA. This can be justified by the fact that the proposed treatment method decreases the total amount of old mortar adhering to RA surfaces, leading to slightly rounded aggregates. Thus, less SP was needed when TRA was
used (Table 1). The tested fresh SCC mixes indicated no signs of segregation on thorough visual inspection, with no mortar halos at the edge of the flow spread.

| Mix notation | Slump flow | J–ring flow test |
|---------------|------------|------------------|
|               | Spread, mm | J500, s | Spread, mm | $S_J$, mm |
| NA-NS         | 710        | 1.3    | 690        | 9        |
| RA-NS         | 685        | 2.1    | 650        | 15       |
| TRA-NS        | 700        | 1.7    | 675        | 10       |
| NA-HS         | 730        | 2.2    | 720        | 8        |
| RA-HS         | 705        | 3.0    | 675        | 13       |
| TRA-HS        | 715        | 2.5    | 700        | 8        |

### 3.2.2 Passing-ability

The passing-ability test is designed to ensure that the produced SCC mixes containing natural, untreated, and treated recycled aggregates could pass the reinforcing bars gaps in real reinforced concrete structural elements. To check this, the J-ring test, based on BS EN 206-9, 2010 [26] specifications, was conducted. SCC passing ability can be assessed as the height difference ($S_J$) between the fresh concrete inside and outside the J-ring apparatus’ steel bars. As the acceptance of passing-ability criterion is that the $S_J$ value is no more than 10 mm [26], Table 3 shows that the SCC mixes made of NA and TRA clearly met the passing ability requirements. However, the mixes with RA (RA-NS and RA-HS) did not satisfy the passing-ability criterion, as their $S_J$ values were greater than 10 mm. Again, due to the particles’ rounder shape, treated RA showed greater passing-ability than RA.

### 3.3. Hardened properties of concrete mixes

#### 3.3.1 Compressive strength

The general performance of a concrete structure can be indicated by its compressive strength ($f_{cu}$) [31]. In RA concrete, this property (under particular conditions) can be affected by several factors including water/cement (w/c) ratio, properties and volume of RA, and adhered mortar attached to RA [6]. From Table 4, the TRA and RA concrete mixes showed lower compressive strength values compared to the control mix. For the mix with 0.57 w/c, the relative compressive strength with respect to the control mix (NA-NS) reached about 82% and 94%, respectively, when RA and TRA were used, while in the mixes with a lower w/c ratio (i.e. 0.35), it reached about 86% and 96%, respectively, compared with the reference mix (NA-HS). However, a comparison between TRA and RA mixes in Table 4 demonstrates that there is a noticeable improvement in the compressive strength of SCC mixes when TRA is used, regardless of the strength grades, although this improvement is less pronounced in mixes with relatively high w/c ratios. The reason for this is the ability of PVA to coalesce and bridge the pores and cracks that exist in the RA matrix. Another reason may also, however, be the removal of the loose old mortar attached to RA surfaces.
3.3.2 Splitting tensile strength
The 28-day splitting tensile strengths \( f_{st} \) of the tested SCC mixes (using cylinders of 100 x 200 mm) are presented in Table 4. The influence of incorporating RA and TRA on \( f_{st} \) was found to be almost similar to that seen on compressive strength. Generally, in comparison with the control mix, the \( f_{st} \) of mixes with RA dropped by 20% and 17% for RA-NS and RA-HS, respectively, whereas it decreased only marginally (about 11% and 8%) for TRA-NS and TRA-HS, respectively. This means that \( f_{st} \) of SCC mixes made from TRA was higher than that of mixes with RA. From Table 4, it can be also noted that the compressive strength test showed that TRA-HS mix presented the lowest loss in splitting strength compared to the corresponding control mix (NA-HS). The improved microstructure of TRA, due to the removal of adhering mortar as well as the filling the internal defects with PVA solution, plays an important role in enhancing the ITZ of TRA [24].

3.3.3 Modulus of elasticity
The Young’s modulus of elasticity (E) of a concrete mix, which measures its stiffness, is generally determined as a function of compressive strength values, and many relationships for both CC and SCC have been developed with respect to this. However, this does not seem to be the case for the RA concrete, specifically when 100% RA is used. The test results presented in Table 4 reveal a remarkable reduction in modulus of elasticity of RA concrete mixes compared to those of NA mixes. In comparison with the control mixes (NA-NS and NA-HS), SCC incorporating RA exhibits 27% and 22% less modulus of elasticity, respectively. This observation is in agreement with previous experimental results [10,15]. It is known that the concrete modulus of elasticity is dominated by the modulus of elasticity of the individual mix ingredients [31]; consequently, inferior modulus of elasticity in a concrete mix containing RA can be expected, due to the increased number of surface cracks and higher porosity than NA [21]. Interestingly, the substitution of RA with TRA has a major positive influence, with increases of about 19% and 17% on the modulus of elasticity for normal strength SCC (TRA-NS) and high strength SCC (TRA-HS) being registered compared with

### Table 4: Hardened properties of test SCC mixes

| Mix notation | Compressive strength \( f_{cu} \) (MPa) | Compressive strength \( f_{cu} \) relative to control | Splitting tensile strength \( f_{st} \) (MPa) | Splitting tensile strength \( f_{st} \) relative to control | Modulus of elasticity (E) (GPa) | Modulus of elasticity (E) relative to control |
|--------------|----------------------------------------|-----------------------------------------------|------------------------------------------|---------------------------------|-------------------------------|-----------------------------------------------|
| NA-NS        | 32.4                                   | 1.00                                          | 3.08                                     | 1.00                            | 30.37                         | 1.00                                          |
| RA-NS        | 26.6                                   | 0.82                                          | 2.46                                     | 0.80                            | 22.17                         | 0.73                                          |
| TRA-NS       | 30.5                                   | 0.94                                          | 2.74                                     | 0.89                            | 27.95                         | 0.92                                          |
| NA-HS        | 53.4                                   | 1.00                                          | 4.11                                     | 1.00                            | 35.10                         | 1.00                                          |
| RA-HS        | 45.9                                   | 0.86                                          | 3.40                                     | 0.83                            | 27.38                         | 0.78                                          |
| TRA-HS       | 51.3                                   | 0.96                                          | 3.78                                     | 0.92                            | 33.35                         | 0.95                                          |
RA-NS and RA-HS, respectively. This confirms the effectiveness of the proposed treatment method.

4. Conclusions

From the results of this study, the following brief conclusions can be drawn:

1. The properties of the treated RA, compared with untreated RA, showed great improvement in terms of water absorption, density, and Los Angeles abrasion. At the maximum PVA concentration (4%), this improvement was only marginally better than that seen at 3%, and thus, the latter can be considered the optimum amount.

2. The produced SCC mixes with TRA were found to satisfy the necessary self-compaction criteria of flow-ability, passing-ability, and segregation resistance.

3. With regard to compressive strength, splitting tensile strength, and modulus of elasticity, SCC mixes made with TRA (compared with RA) showed general improvements in their hardened properties, irrespective of the mix w/c ratio; however, the improvement was more pronounced in SCC mixes with relatively low w/c ratios.

4. The experimental results of this research are promising and confirm that the proposed treatment method is a simple and dependable way to enhance RA properties to allow it to be successfully used in self-compacting concrete.

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