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Shaikh, Odoh and Than

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# Effect of nano silica on properties of concretes containing recycled coarse aggregates

Faiz Uddin Ahmed Shaikh MEng, PhD

Senior Lecturer, Department of Civil Engineering, Curtin University, Perth, Australia

Heasam Odoh BEng

Final year project student, Department of Civil Engineering, Curtin University, Perth, Australia

Andrew B. Than BEng

Final year project student, Department of Civil Engineering, Curtin University, Perth, Australia

The effect of nano silica on mechanical and durability properties of concretes containing recycled coarse aggregates (RCA) is investigated using seven series of concretes: the first is the control series, containing all natural aggregates and no nano silica. In the second and third series, 25% and 50% (by weight) natural coarse aggregates are replaced by RCA, respectively. Effects of nano silica on concretes containing RCA are evaluated in the remaining series: in the fourth and fifth, 1% and 2% (by weight) nano silica is added to concrete containing 25% RCA, respectively. Similar nano silica additions are used in the sixth and seventh series, but the RCA content is 50%. Compressive and tensile strengths of all concretes are evaluated after 7, 28 and 56 d of water curing. Concrete durability properties, such as sorptivity, volume of permeable voids and chloride penetration, are also evaluated after 7 and 28 d of water curing. Addition of nano silica is found to significantly improve compressive strength of concrete containing 25% RCA at all ages; however, no such improvement is observed in concrete containing 50% RCA. An opposite scenario is observed for tensile strength, where nano silica addition showed improvement in concrete containing 50% RCA. The addition of nano silica also exhibited improvement in the durability properties of concretes containing 25% and 50% RCA.

## 1. Introduction

The substantial amount of construction and demolition wastes generated annually requires huge land area to dump and this contributes to environmental problems worldwide (Kwan *et al.*, 2012). Additionally, extraction of natural aggregates is adversely affecting the global environment as the utilisation of concrete is increasing annually. The disposal of construction and demolition wastes is becoming a major social issue that has prompted many researchers worldwide to investigate new means of recycling it, with the aim of alleviating the pressure on the scarce landfill space available and also as a means to reduce the current reliance on natural aggregates and minerals (Kou *et al.*, 2012; Tabsh and Abdelfatah, 2009; Zaharieva *et al.*, 2003). Given that coarse and fine aggregates occupy 75–80% of the total volume of the concrete (Lamond and Pielert, 2006), the incorporation of construction and demolition wastes in the form of recycled coarse aggregates (RCA) has huge potential (Corinaldesi and Moriconi, 2009) and, although this is not a new concept, many researchers around the world have investigated the resulting properties: there is wide agreement that RCA concrete presents inferior properties in comparison to conventional concrete

incorporating natural aggregates (Corinaldesi and Moriconi, 2009; Etxeberria *et al.*, 2007; Shaikh, 2013; Shaikh and Nguyen, 2013).

The drawbacks exhibited by RCA have been attributed to the presence of old mortar/paste and fissures formed during the manufacturing or crushing of RCA, which makes the aggregates more susceptible to fluid transportation of dissolved solid ions (Etxeberria *et al.*, 2007; Kou *et al.*, 2012) and hence the immediate impact on the concrete properties. From investigations of the properties of concrete containing RCA at various substitution levels, results have shown certain characteristics, including a weaker interfacial transition zone between the cement paste and the RCA and an increase in permeability. Significant research studies based on mechanical and durability performance of concrete incorporating RCA have recommended a substitution range of 20–30%, because replacements within this range have been found to show minimal influence on the overall performance of the concrete (Kou *et al.*, 2011; Kou and Poon, 2012; Kwan *et al.*, 2012; Thomas *et al.*, 2013), thus highlighting the feasibility and potential to solve the current environmental issues.

Although the above findings are significant in indicating the feasibility of its incorporation in concrete, the lack of proper jurisdictions to allow its incorporation in structural applications has limited the use of RCA in Australia as a whole. Its current and most common applications include concrete kerbs and gutter mix, granular base coarse material, embankment fill materials, paving blocks, backfill material and building blocks. Other researchers have investigated the use of supplementary cementing materials and their results showed reduction in porosity and enhanced properties of the recycled aggregate concrete. Silica fume, metakaolin and fly ash are among the most widely used additives (Ahmed, 2013; Ali *et al.*, 2012; Ann *et al.*, 2008). Their use and incorporation improves the mechanical and durability properties through what Kong *et al.* (2012) described as the triple mechanisms, as listed below.

- (a) They act as fillers to fill the voids between the cement particles which would otherwise be occupied by water.
- (b) They chemically react with calcium hydroxide to produce calcium-silicate-hydrate (C-S-H) gel, thus reducing the total porosity of the matrix, and improve the interfacial transition zone properties.
- (c) They act as seeds to provide nucleation sites for cement hydration products.

Over recent years a new supplementary cementing material called nano silica (NS) has emerged on the market and has attracted many researchers across different fields, mainly owing to its high silicon dioxide ( $\text{SiO}_2$ ) content and its nano-size particles (Jo *et al.*, 2007; Senff *et al.*, 2009; Shaikh *et al.*, 2014; Supit and Shaikh, 2014; Supit *et al.*, 2013). Literature suggests that NS reacts with the calcium hydroxide of cement hydration and forms calcium-silicate-hydrate gel which fills the interconnected pores and alters their distribution. This in turn reduces the porosity of the concrete matrix and increases its permeability resistance. Additionally, it behaves as a nucleus that tightly bonds with cement hydrate, forming a stable gel structure which shows closer packing (Ji, 2005). With the current research findings indicating significant early strength gain in conventional concrete, there are strong grounds to believe that NS could successfully be used and incorporated in recycled aggregate concrete to compensate the loss in mechanical strength and to improve the durability properties. Given the potential indicators in early age strength gain and general refinement to the internal structure, the objective of the present research is to investigate the influence of NS addition on the mechanical and durability properties of concrete containing RCA. Although the research investigated only few properties relating to the use of NS to improve the mechanical and durability properties of recycled aggregate concretes, it provides a good platform for future work in this field.

## 2. Experimental programme

### 2.1 Materials

General purpose Portland cement was used in all mixes. The NS was obtained from Nanostructured and Amorphous Materials, Inc., USA, with average particle dia. of 25 nm and surface area of  $160 \text{ m}^2/\text{g}$ . The NS was in powder form with purity of 99% silicon dioxide ( $\text{SiO}_2$ ). The specific gravity was within the range of 2.2–2.6 (Shaikh *et al.*, 2014). Prior to its addition to the mix, the mix quantity for 1% and 2% NS additive was added into 1 litre of water containing superplasticiser and this was placed in an ultrasonic dispersion machine, as shown in Figure 1, for 30 min to disperse the

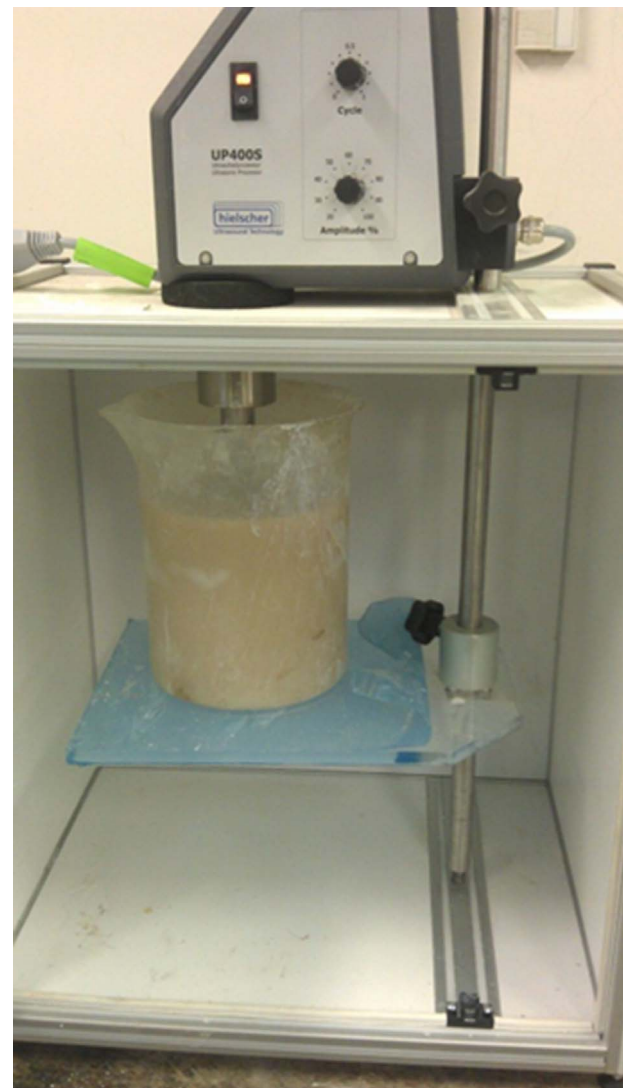


Figure 1. Dispersion of nano silica in water containing superplasticiser during ultrasonication

Mix proportions: kg/m<sup>3</sup>

Series	NS	RCA	NCA (20 mm)	N (10 mm)	Fine aggregate (sand)	Cement	Water	Superplasticiser
Control	0.0	0.0	405.0	810.0	654.0	430.0	172.0	0.0
R25N0	0.0	303.8	303.8	607.5	654.0	430.0	172.0	0.0
R25N1	4.3	303.8	303.8	607.5	654.0	430.0	172.0	2.2
R25N2	8.6	303.8	303.8	607.5	654.0	430.0	172.0	4.3
R50N0	0.0	607.5	202.5	405.0	654.0	430.0	172.0	0.0
R50N1	4.3	607.5	202.5	405.0	654.0	430.0	172.0	2.2
R50N2	8.6	607.5	202.5	405.0	654.0	430.0	172.0	4.3

**Table 1.** Mix proportions

particles evenly and to prevent the formation of NS agglomerates when added to the concrete mix. Rheobuild 1000, high-range water reducer was added to mixes containing NS at a rate of 0.5% of cement for mixes containing 1% NS, and 1% of cement for mixes containing 2% NS. The quantities used are detailed in Table 1.

The RCA was obtained from a local construction and demolition waste recycling plant in Perth, Western Australia. Table 2 shows the analysis of contents of a 5 kg sample of the construction and demolition waste used as RCA in this study. It can be seen that approximately 75% is concrete and the rest consisted of masonry, asphalt and other materials. The properties of recycled and natural aggregates are shown in Table 3. As expected the RCA has higher water absorption, lower bulk density and more than acceptable amounts for brick content according to Australian standard AS 155:2002 (Standards Australia, 2002); however, it also met the grading requirements for concrete aggregates specified in the Australian standard AS 2758.1:1998 (Standards Australia, 1998) (Figure 2). Both recycled and natural course aggregates were soaked in water for 48 h, washed thoroughly to remove impurities and dried afterwards to maintain the saturated surface dry (SSD) condition.

## 2.2 Mix proportions

In total, seven series of mixes were considered in this study. The first series was a control mix containing 100% natural coarse aggregates. The second, third and fourth mixes were

Constituents of recycled aggregates: %

Sample	Concrete	Brick	Asphalt	Others
1	78	6	5	11
2	72	9	5	14
3	75	7	5	13
Average	75	8	5	12

**Table 2.** Constituents of RCA used in this study

concrete containing 25% RCA that contained 0%, 1% and 2% NS; these are termed R25N0, R25N1 and R25N2, respectively. Similarly, the fifth, sixth and seventh series were concrete containing 50% RCA and contained 0%, 1% and 2% of NS, respectively. The mix proportions of all the mixes are shown in Table 1. The 1% and 2% NS contents used in this study were based on the authors' recent study on the effect of NS on early age compressive strength of ordinary and high-volume fly ash concretes (Shaikh *et al.*, 2014), where 2% NS was found to be the optimum content.

## 2.3 Concrete casting and curing

All concretes were mixed in a pan mixer using constant water-to-binder ratio of 0.4. As mentioned earlier, the NS was first ultrasonically dispersed in water containing superplasticiser and was added to the mix during mixing along with remaining water. Slump tests were done immediately after mixing the concrete to measure the workability of each mix. At least three specimens were cast and tested in each series. All specimens were water cured until the day before the test date.

The compressive strength and indirect tensile strength were measured at 7, 28 and 56 d, while the water sorptivity, chloride permeability and volume of permeable voids (VPV) were measured at 7 and 28 d in each series. The compressive strength test was carried out on 100 mm dia. × 200 mm cylinders and the indirect tensile strength was determined on 150 mm dia. × 300 mm cylinders. The 100 mm dia. × 200 mm cylinder was cut into three 50 mm thick slices and was used in water sorptivity, chloride

Properties measured	RCA	NCA	Fine aggregate
Water absorption: %	4.2	0.8	3.2
Uncompacted bulk density: kg/m <sup>3</sup>	1180	1490	–
Compacted bulk density: kg/m <sup>3</sup>	1460	1760	–

**Table 3.** Properties of NCA and RCA

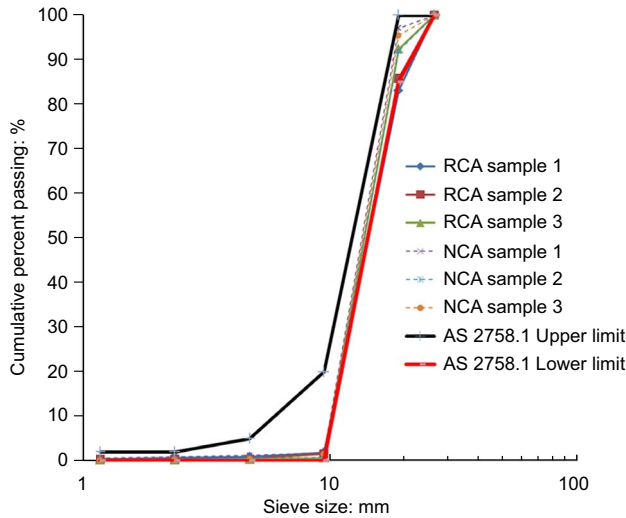


Figure 2. Sieve analysis of RCA and NCA

permeability and VPV tests. The compression and tensile tests were conducted in accordance with relevant Australian standards (AS 1012.21:1999 (Standards Australia, 1999a) and AS 1012.3.1:1999 (Standards Australia, 1999b)).

### 2.3.1 Water sorptivity

The rate of water absorption (sorptivity) of concrete samples with 50 mm thick disk was determined at 7 and 28 d according to ASTM C1585-13 (ASTM, 2013). The principle of the method is that a specimen has one surface in free contact with water (no more than 5 mm above the base of the specimen) while the other sides are sealed. This test determined the rate of absorption of water by hydraulic cement concrete by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time. In this study, the mass of the concrete specimen was regularly measured to determine the initial absorption from 1 min to the first 6 h. The absorption ( $I$ ) was the change in mass divided by the product of the cross-sectional area of the test specimen and the density of water. The initial rate of water absorption value ( $\text{mm/s}^{1/2}$ ) was calculated as the slope of the line that is the best fit to  $I$  plotted against the square root of time ( $s^{1/2}$ ).

### 2.3.2 Volume of permeable voids

This test was conducted to estimate the percentage of voids present in the concrete specimens after curing at 7 and 28 d, based on AS 1012.21:1999 (Standards Australia, 1999a). The VPV is determined by boiling the 50 mm cut concrete specimens for at least 5 h in a water tank at 105°C and weighing the sample in water, then measuring the percentage of voids with dried mass and mass in the water.

### 2.3.3 Chloride penetration

The chloride depth penetration test was conducted in accordance with the method proposed by Otsuki *et al.* (1993). The method is easy to perform and physically shows the penetration depth of chloride upon spraying with silver nitrate solution. The procedure included cutting 100 mm dia. cylindrical samples into 50 mm thick slices after they had been cured for 7 and 28 d, the sides were sealed with a silicone sealant, exposing only one cylindrical surface in order to permit the ingress of external chloride ions in a single direction. The sectioned samples were later immersed in a 3% sodium chloride solution (by weight) and were laid out in a container with the water level being 20 mm above the top surface. A minimum of two samples were prepared for each series at the specific curing age highlighted above.

The samples were immersed in the solution for a total period of 28 d before the samples were taken out, cut in half and left to air dry under laboratory conditions. A 0.1N silver nitrate solution was used to spray the cut surface of each slice as it was examined, to give the most distinctive colour change boundary – indicated by a white precipitate resulting from the formation of silver chloride on the surface and a brown colour where no chloride salt had penetrated. After spraying the samples, they were left overnight so that the colour change boundary was well defined; they were then marked out using a pen to allow the boundary to be more easily distinguished. Five readings were then made at the locations depicted in Figure 3; these were then averaged to give the penetration depth of the chloride ions for each specimen at the particular curing age.

## 3. Results and discussion

### 3.1 Compressive strength

Figure 4 shows the effect of 25% and 50% RCA on compressive strength of ordinary concrete as well as addition of 1% and 2% NS on the above recycled aggregate concretes. It can be seen that the 25% and 50% replacements of natural coarse aggregate (NCA) with RCA exhibited a reduction in compressive strength compared to the control concrete. The figure also shows that in concrete containing 25% RCA, the addition of 1% and 2% NS significantly increased the compressive strength at all ages. It is

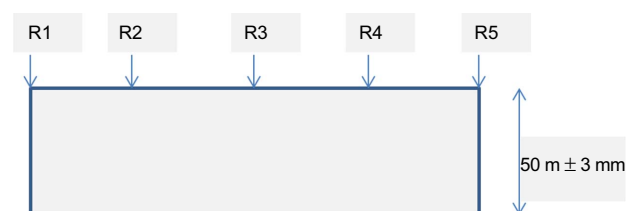


Figure 3. Locations of measurements made on each sample

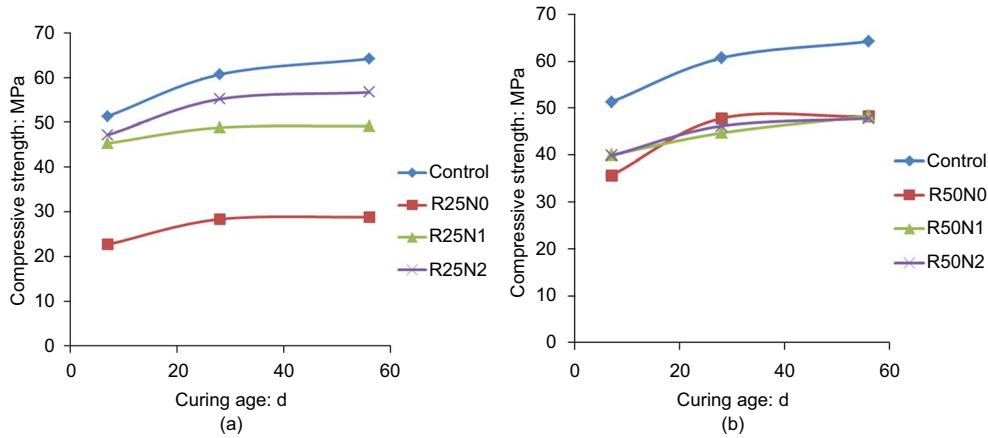


Figure 4. Effects of NS on compressive strength development of concretes containing (a) 25% and (b) 50% RCA

also observed that the 2% NS performed slightly better than 1% NS in concrete containing 25% RCA. The 7-d compressive strength is doubled in R25N1 and R25N2 concretes. It is also observed from the results that the compressive strength still increased by 70–90% at 28 and 56 d owing to addition of NS to concrete containing 25% RCA. This could be attributed to the secondary hydration reaction of the NS with calcium hydroxide (CaOH<sub>2</sub>) and the formation of additional calcium-silicate-hydrate. The significant strength enhancement at early age (7 d) by NS is due to its extremely high surface area and fineness, which accelerated its early reaction with calcium hydroxide, as observed by the authors (Shaikh *et al.*, 2014).

The results of concretes containing 50% RCA, however, were not consistent with those containing 25% RCA. It was

observed that the compressive strengths of concrete containing 50% RCA still increased when 1% and 2% NS was added to the concrete, but only marginally, and in fact the strength slightly decreased at 28 d as compared to R50N0. In mix R50N2 the results at 28 and 56 d did not seem to show increased compressive strength over R50N0, although an addition of 2% of NS was considered. However, the early age strength enhancement due to NS additions can still be seen in concrete containing 50% RCA, but at a low rate.

### 3.2 Tensile strength

The effects of NS addition on the tensile strength of recycled aggregate concrete are shown in Figure 5. It can be seen that the tensile strength decreased as RCA was increased in the concrete mix, which was similar to the compressive strength

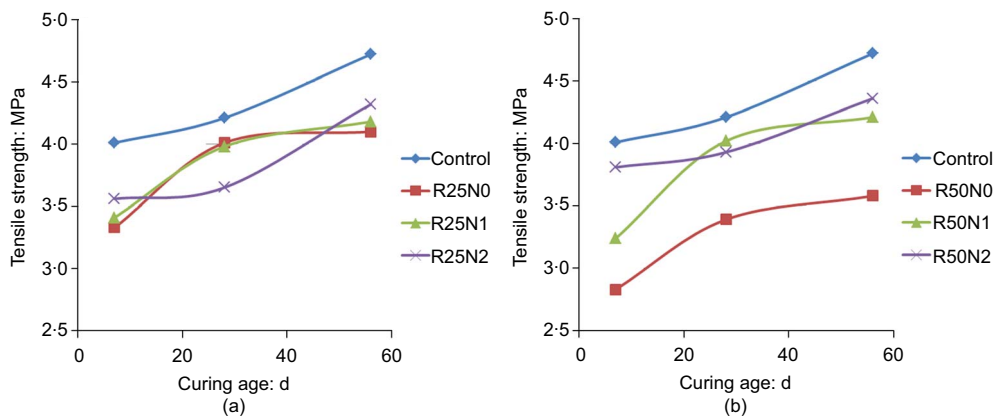


Figure 5. Effects of NS on tensile strength development of concretes containing (a) 25% and (b) 50% RCA

results. The tensile strength was decreased by about 5–17% and 19–29% when 25% and 50% RCA, respectively, were used to replace natural coarse aggregates.

Similar to the compressive strength, the tensile strength of all recycled aggregate concretes increased with curing, but the trends are different when the addition of NS is considered. When comparing the effect of NS addition to the concrete containing 25% RCA, the mixes R25N1 and R25N2 show marginal increase, between 2 and 7%, in 7-d tensile strength. However, at 28 and 56 d, the addition of NS also slightly increases the tensile strength. In the case of concrete containing 50% RCA, samples with the addition of 1% and 2% NS surprisingly performed better than concrete samples containing 25% RCA, with about 14% and 35% improvement at 7 d, respectively. The 28- and 56-d tensile strength of those concretes also increased due to NS addition.

### 3.3 Volume of permeable voids

The VPV of concrete gives an indication of its durability related to permeability, absorption, etc. The results of VPV are affected by a number of factors including compaction, curing, air entrainment, absorption and physical nature of the aggregate used (AS 1012.21:1999 (Standards Australia, 1999a)). It can be observed from the VPV results shown in Figure 6 that the percentage of voids in concrete increases as the amount of RCA increases without NS addition and decreases with curing. The inferior properties of RCA are translated into the concrete specimens; it can be seen from the results that the volume of voids increases by 15% and 37% for concrete containing 25% and 50% RCA, respectively at 28 d, with the results being slightly lower, at 13% and 27%, for 7 d compared to the control. The increase in VPV of R25N0 and R50N0 concretes compared to the control concrete can be attributed to the higher porosity

of RCA than NCA. The higher water absorption of RCA compared to NCA shown in Table 3 is also an indication of higher volume of pores/voids in recycled aggregate concretes.

The effect of the addition of 1% and 2% NS on VPV of recycled aggregates concretes can also be seen in Figure 6. It can be seen that there is no change in the volume of voids in concrete containing 25% RCA due to 1% and 2% NS addition. In contrast, the concrete containing 50% RCA, however, exhibited about 7% and 11% reduction in VPV at 7 d and 4% reduction in VPV at 28 d due to addition of 1% and 2% NS, respectively. Although it could be said that NS does improve the hydration, and hence the microstructure, these results indicate no significant improvement and, without any further research to investigate the microstructure of the concrete at different replacements, a conclusion cannot be drawn as to why NS did not have a more profound effect on the reduction of VPV.

### 3.4 Sorptivity

The rate of absorption of water by concrete is a function of the penetrability of the pore system, where for unsaturated concrete the rate of ingress of water or other liquids is largely controlled by absorption due to capillary rise. This is dependent on many factors, including the concrete mix proportions, presence of chemical admixtures and supplementary cementitious materials, the entrained air content, curing age, presence of micro cracks, presence of surface treatment such as sealers, the placement method including compaction and finishing, and also by the moisture condition of the concrete at the time of testing (ASTM C1585-13 (ASTM, 2013)).

Figure 7 summarises the effect of RCA substitution and NS addition on the sorptivity of concretes measured after 7 and

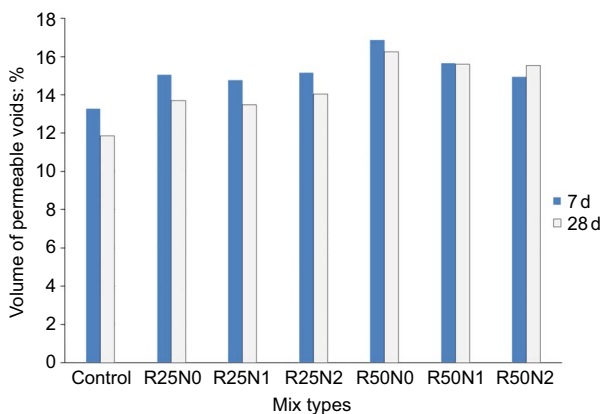


Figure 6. Effects of NS on volume of permeable voids of concretes containing 25% and 50% RCA

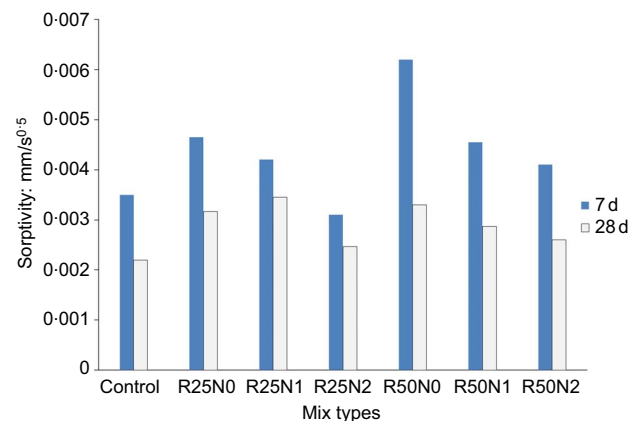


Figure 7. Effects of NS on water sorptivity of concretes containing 25% and 50% RCA

28 d of curing. It is evident from the figure that the substitution of RCA significantly increases the sorptivity of the concrete: for example, for R25N0 and R50N0 concretes the sorptivity increased by 33% and 77% at 7 d curing and 44% and 50% at 28 d relative to the control concrete. This increased absorption due to capillary rise is expected and is due to the inferior properties of the RCA, such as higher water absorption than NCA (refer to Table 3). The higher water absorption of the RCA is primarily linked to the attached mortars on its surface which are very porous and also the high percentage of masonry products (Sagoe-Crentsil *et al.*, 2001). Furthermore, given the nature of the RCA manufacturing process, it tends to form cracks and fissures in the aggregate which further contributes to increased sorptivity of the concrete.

It can also be seen that the water sorptivity reduced with curing age, due to a continual hydration process of the cement that reduces capillary spaces and densifies the microstructure, thereby retarding the fluid flow in the concrete. Although the test has been conducted at early ages of the concrete samples, it can be seen that there is a reduction in sorptivity of R25N0 and R50N0 concretes from 7-d curing to 28-d curing; however, the sorptivity is still higher than that of the control concrete. The reduction of sorption with curing is attributed to the formation of new calcium-silicate-hydrate that further densifies the matrix and blocks the interconnected pores within the concrete, which thus leads to lower sorption. In contrast, it can be seen that the addition of NS significantly reduces the sorptivity of recycled aggregate concretes, specifically at early ages (7-d curing) as can be seen in Figure 7. It can be seen in Figure 7 that the sorptivity is decreased by 10% and 17% for R25N1 and R50N1 concretes, respectively and 33% and 34% for R25N2 and R50N2 concretes, respectively at 7 d. On the other hand, at 28 d the sorptivity is only 9% higher and 22% lower for R25N1 and R25N2, respectively and 13% and 21% lower for R50N1 and R50N2, respectively. The 25% RCA series in particular displayed promising results for 2% NS addition, exceeding the control at 7 d due to increased hydration and at 28 d it was only 12% higher relative to the control, and therefore further curing may allow it to exceed the resistance of the control concrete if this aspect was to be investigated.

It can thus be seen that the NS offers exceptional reduction of sorptivity at early age, and the improvements are linked to its ability to enhance the internal structure because it is able to refine the pore structure and improve the permeability resistance by way of a triple mechanism; this mechanism includes the NS acting as a nucleus that tightly binds the calcium-silicate-hydrate gels, also reacting with calcium hydroxide to further promote the formation of calcium-silicate-hydrate gels, and finally acts as particle packing to block the interconnected pores within the system (Kong *et al.*, 2012).

### 3.5 Chloride penetration depth

Chemical attack on concrete structures is one of the primary reasons for its degradation, as a result of the ingress of chloride ions that penetrate into the concrete cover then chemically react to form rust around the reinforcement, spalling the concrete and causing a premature end to the structure's life cycle. This process, however, is very slow and is subject to many factors such as external environment, water-to-cement ratio of the concrete, depth of concrete cover and the concentration of chloride in the external media.

It is claimed by some researchers that the chloride ion resistance of concrete depends largely on the porosity and inter-connectivity of the pore system and to a lesser extent on the chemical binding capacity of the cement (Thomas *et al.*, 2013). In Figure 8, it can be seen that upon the partial substitution of RCA, the concrete is more susceptible to the ingress of ions; for the R25N0 and R50N0 series at 7 d of moist curing, there is an 18% and 21% increase in chloride penetration depth and at 28 d, a further increase of 25% and 33% relative to the control sample. This decreased resistance was anticipated, given that RCA had higher water absorption (shown in Table 3) and porosity due to the adherence of mortar on the surface that is highly permeable, and also due to the masonry content, as can be seen in Table 2.

In Figure 8, it can be seen that the curing age has a significant effect on the resistance of all series due to the hydration of cement, which further produces calcium-silicate-hydrate gels; however, the R25N0 and R50N0 concretes exhibited inferior performance as the penetration depths were still significantly larger at both 7- and 28-d curing ages relative to the control. It can be seen in Figure 8 that, as the amount of NS increased, so did the concrete's resistance, where for 1% and 2% addition

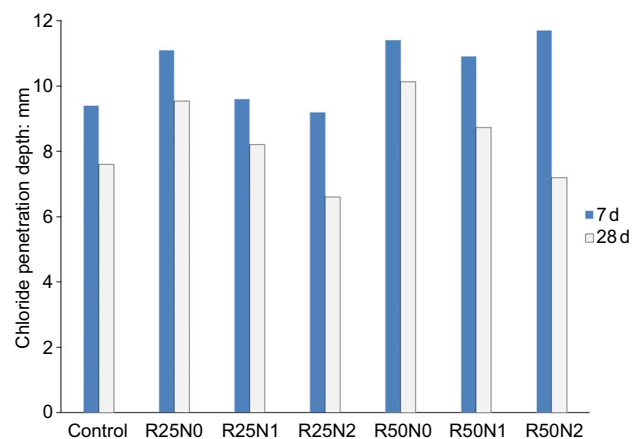


Figure 8. Effects of NS on chloride penetration depth of concretes containing 25% and 50% RCA

there is a relative decrease of 14% and 31%, respectively for the 25% RCA substitution and 14% and 29%, respectively for the 50% RCA series at 28 d of curing.

Although it is well established that the increased hydration of concrete induces the self-desiccation of the cement paste, causing the capillary spaces to become narrower and enabling the formation of calcium-silicate-hydrate gel, so the number of connected pores decreases (Thomas *et al.*, 2013), it is also known that longer curing results in the self-healing phenomenon, and the higher the fraction of old mortar attached or bonded to the RCA, the higher the amplification of self-healing, which has the potential to decrease the water permeability of RCA concrete in the long term (Levy and Helene, 2004). It can also be seen from the figure that the addition of 1% NS in concrete containing 25% RCA is sufficient to produce concrete that is able to perform better than the control and at 2% NS addition it is in fact able to exceed the resistance provided by the control concrete for both the 25% and 50% RA substitution series. It should also be noted that these results are highly variable, mainly due to the randomness of RCA distribution within the actual test specimen and the variation of RCA contents in construction and demolition wastes.

#### 4. Conclusion

Based on experimental evidence from the present study on the effect of nano silica on the mechanical and durability properties of concrete, the following conclusions can be drawn.

- The addition of NS increased the compressive strength of concretes containing 25% and 50% RCA at all ages up to 56 d. The improvement of compressive strength is higher in concrete containing 25% RCA than for that containing 50% RCA. Concrete containing 25% RCA and 2% NS achieved 92% of the control concrete's compressive strength at 28 to 56 d. With prolonged curing, this gap can be reduced further.
- The addition of NS increased the tensile strength of recycled aggregate concretes. Both recycled aggregate concretes also achieved more than 90% of the control concrete's tensile strength at 28 d.
- It could be observed from VPV results that the addition of NS reduced the volume of permeable voids in recycled aggregate concretes at both 7 and 28 d, with significant reduction at 7 d. When compared to the control concrete, no reduction in volume of permeable voids is noticed in either of the recycled aggregate concretes due to the addition of NS.
- In both recycled aggregate concretes the sorptivity is much lower at 28 d than at 7 d due to the addition of NS and the long curing time. The increased addition of NS decreased the sorptivity of recycled aggregate concretes, and at 25% RCA replacement it showed even better resistance than the

control concrete, reducing the sorptivity by 11% after 7 d of moist curing.

- It is suggested from the results that increased addition of NS tends to increase the chloride ion resistance of the concrete, given that it acts to promote the hydration and block the capillary spaces within the concrete. The 2% addition of NS decreased the chloride penetration depth of concretes containing 25% and 50% RCA by 31% and 28%, respectively at 28 d and, when compared to the control concrete, it displayed better resistance and exceeded it by 13% and 5%, respectively at 28 d. In addition, curing age made a substantial difference to the resistance across all series; however, the difference was more significant for the series incorporating NS.

Although further studies are necessary to better understand the influence of NS on recycled aggregate concretes, it could be suggested from the results that using NS is a promising approach to improve both the mechanical and durability properties of concrete and hence its performance. Furthermore, it is suggested from the conducted tests and results at this stage, and in accordance with the limitations of this research, that 2% NS addition to concrete containing RCA from construction and demolition wastes can produce structural grade concrete that is able to perform without any drawbacks to its mechanical and durability properties. The early age strength gain promoted by the addition of NS could also suggest the use of NS in conventional concrete to allow for earlier formwork stripping time, in addition to better mechanical and durability performance if exposed to harsh environmental conditions.

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