EXPERIMENTAL STUDY ON THE PROPERTIES OF RUBBERISED CONCRETE INCORPORATING NANO-SILICA

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الملخص

يتناول هذا البحث دراسة حول تأثير إضافة النانو سيليكا (NS) على الخواص الميكانيكية للخرسانة المضاف إليها المطاط. حيث أُعِدَّتْ خلطات تم فيها استبدال الركام الناعم حجمياً بنسب 0%، 10%، 20 % و 30% بالمطاط وكانت نسب الماء للإسمنت ثابتة لكل الخلطات = 0.45. بينما كانت نسب إضافة النانو سيليكا إلى الإسمنت بالوزن 0%، 1.5% و 3%. وأجريت الاختبارات على هذه الخلطات والتي تشمل دراسة الخواص الأساسية مثل الكثافة ونسبة الامتصاص ومقاومة الضغط والشد ومقاومة الإنحناء والانكماش. أثبتت النتائج أن استخدام النانو سيليكا قد عزز من خواص مقاومة الخرسانة المضاف إليها المطاط بينما في المقابل قلل من الانفعال الناتج عن الانكماش.

ABSTRACT

This research investigates the effect of incorporating nano-silica (NS) on the mechanical properties of rubberised concrete. Fine aggregate was replaced with rubber at a ratio of 0%, 10%, 20% and 30% by volume. A constant water to cement (w/c) ratio of 0.45 was used in all concrete mixes. The influence of incorporating 0%, 1.5% and 3% of nano-silica (NS) to cement by weight on the basic properties of rubberised concrete, including density, water absorption, compressive strength, flexural strength, splitting tensile strength and drying shrinkage of samples, was studied. The results showed that the utilisation of NS in the rubberised concrete mixes enhanced the strength properties and decreased the drying shrinkage strain.

KEYWORDS: Rubberised Concrete; Nano-Silica; Density; Porosity; Water Absorption; Strengths.

INTRODUCTION

The accumulation of waste tyres has become one of the most vital problems as a source of environmental pollution across the world. One of the possible solutions to tackle this problem is to incorporate the waste tyres into concrete, to partially replace natural fine aggregates. Over the last two decades, the use of waste tyres has gained considerable interest in concrete technology.

There are several benefits of rubberised concrete, compared to normal concrete such as lower density [1, 2], higher ductility [3], higher impact resistance [4], better resistance to chloride penetration [5], lower thermal conductivity [6], and a higher noise reduction factor than conventional concrete [7]. On the other hand, the main drawback of rubberised concrete is the reduction in mechanical properties, including compressive strength, flexural strength, splitting tensile strength, and Young's modulus [8-10]. This reduction in strength may be attributed to the weak bond between cement paste and rubber particles [11] and significant variation between the Young’s modulus of rubber aggregates and hardened cement paste [12]. Therefore, many techniques to enhance the strengths of rubberised concrete were explored in the literature [13-15] to enhance the mechanical properties of rubberized concrete. One of these techniques is the chemical pre-treatment of the rubber particles to minimize the loss in strength [13, 14, 16].

Generally, previous research has suggested various methods of modifying the surface of rubber particles, such as the immersion of rubber particles in sodium hydroxide (NaOH) solution to excess its adhesion to the surrounding cement paste [14, 17] and others found that treating the rubber in sulphuric acid (H_2SO_4) can increase the modulus of elasticity of rubber particles [18]. However, researchers observed that the pretreatment of rubber particles has led to a slight enhancement in the compressive strength of rubberised concrete [19]. On the other hand, other researchers suggested that the strengths of rubberised concrete can be enhanced by using supplementary cementitious materials (SCMs) such as silica fume (SF) and nano-silica (NS). It was shown that the addition of SF can improve the compressive strength of rubberised concrete owing to the enhancement of the interfacial transition zone (ITZ) bonding and the reduction of the pore size in the cement paste [8, 11, 20]. Recently, Mohammed et al. [21] observed that incorporating nano-silica into rubberised concrete showed a reasonable improvement in the compressive strength.

Very little literature is available on the effect of incorporating nano-silica on the mechanical properties of rubberised concrete. Because of this limited number of studies, an experimental study was conducted to investigate and confirm the effect of incorporating nano-silica on various properties of rubberised concrete.

EXPERIMENTAL PROGRAMME

Materials

Ordinary Portland cement (OPC, CEM I/ 52.5R) was used as a binder in this research, the physical and chemical properties are shown in Table 1) which complies with the requirements of BS EN 197-1. Moreover, uncrushed gravel was used as coarse aggregate (CA) with a maximum size of 10 mm and natural sand with a maximum size of 5 mm was used as fine aggregate (FA). The physical properties of coarse aggregate, fine aggregate, and rubber are shown in Table (2), and Figure (1a), respectively. The particle size distributions of both aggregates and rubber are within the limits of ASTM/C33M [22].

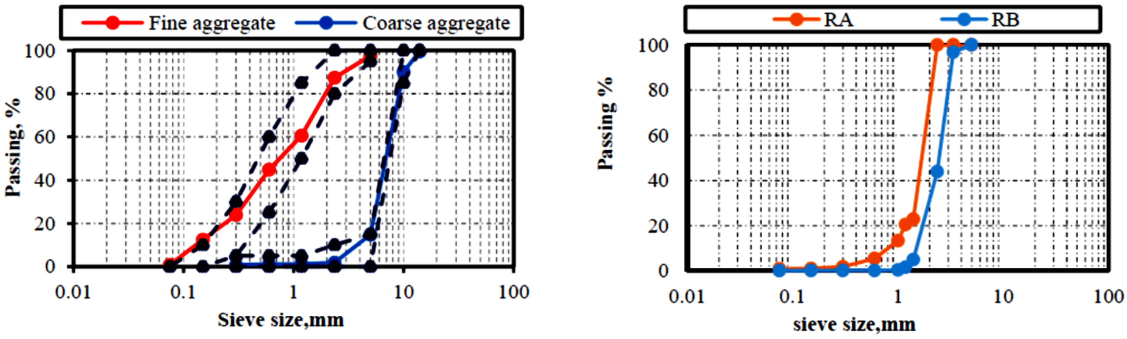
Table 1: Physical and chemical properties of cement.

Chemical compositions		Physical Characteristic	
Oxides, %	Cement	Property	Cement
SiO_2	20.10	Specific gravity	3.15
AL_2O_3	5.04	Blaine fineness(m^2/kg)	400
Fe_2O_3	2.28	Initial setting time (Mins)	150
C_aO	36.24	28 compressive strength, MPa	60
M_gO	2.50		
SO_3	3.39		
Na_2O	0.28		
K_2O	0.62		
Cl	0.05		
loss of ignition	2.87		

Table 2: Physical properties of coarse aggregate, fine aggregate and rubber

Property	**Coarse aggregate**	**Fine aggregate**	**Rubber A**	**Rubber B**
Specific gravity	2.63	2.6	1.19	1.26
Bulk density	1686	1592	726.5	776
Water absorption	0.98	4.5	726.5	5.95

Two size ranges of crumb rubber aggregates were used: RA (0.5 mm - 1.5 mm) and RB (1.5 mm – 3.0 mm). These particular sizes have been chosen as they are close to the size of fine aggregate particles. The physical properties of RA and RB are listed in Table (2), and the sieve analysis results are demonstrated in Figure (1b). The results in Table (2) showed that the rubber particles had a relatively higher water absorption in comparison to that of fine aggregate. It was also observed that the bulk density of all rubber particles was low. This could be due to the lower specific gravity of the rubber. Amorphous nano-silica (NS) with a specific surface area of 250 $\mathrm{m^2/g}$, particles average size of 11 nm and a colloidal suspension form, was used in this study. To obtain the desired workability of the concrete mixture, the superplasticiser (Glenium) 51 was used as a high range water reducer (HRWR), in accordance with BS EN 934-2.



(a) (b)

Figure 1: Grading curves; (a) coarse aggregate and fine aggregate, (b) rubber

Mix design, casting and curing of concrete

One control mixture was designed using the method documented in the ‘Design of Normal Concrete Mixes’[23]. In this paper, all concrete mixtures were designed with constant (w/c) of 0.45 with the total cement content of 500 $\mathrm{kg/m^3}$. The replacement ratio of nano silica (NS) for concrete mixes was 0%. 1.5% and 3.0% by weight of cement. Two different sizes of rubber particles, RA and RB, were used to replace 10%, 20% and 30% of fine aggregates by volume. The main reason for volume replacement of fine aggregate instead of mass replacement is due to the variance between the densities of fine aggregates and rubber particles (see Table (2)). Density of rubber is less than half of fine aggregate density. Details of concrete mix proportions are given in Table (3).

All procedures related to mixing and curing were kept the same for all mixes, except for replacing fine aggregate with an equivalent amount of rubber and cement with the required quantity of NS. It is important to mention that the mixing water was adjusted based on the amount of water present in the colloidal nano-silica . Firstly, NS was mixed with water for 2 min to avoid the agglomeration of nano silica particles, and to ensure the particles of nano-silica are uniformly dispersed. Then, the amount required of SP was added to the solution for another 1 min in order to maintain the workability. Meanwhile, in order to improve the bond between the rubber particles and the cement paste, a unique mixing procedure was followed after several trials. First, cement paste with 20% of the total quantities of cement and water were prepared as a slurry and then the rubber particles were added and mixed for 1 min. After that, the sand was introduced into the mixer and mixed for another 1 min (to allow the sand to cover the rubber particles which may improve the bond between the rubber and the cement paste). Afterwards, the coarse aggregate and the rest of the cement were added and mixed for 1 min. Then, the solution was immediately added to concrete ingredients and mixed for another 2 minutes. To prevent water loss during the mix period, the top of the mixer was covered in accordance with ASTM/C192/C192M [24]. After casting, all specimens were covered with a polyethylene sheet for 24 hours to prevent moisture loss and left at room temperature before they were demoulded. Finally, all specimens were placed in water tanks until the day of the test.

Table 3: Mix proportions of concrete

	Mixture	R (%)	NS (%)	Mix proportions (kg/m^3)						
				C	CA	FA	W	R	NS	SP
Mix1	R0-NS0	0	0	500	731.9	675.6	225	0	0	0
Mix2	R0-NS1.5	0	1.5	492.5	731.9	675.6	225	0	7.5	0
Mix3	R0-NS3	0	3	485	731.9	675.6	225	0	15	0
Mix4	RA10-NS0	10	0	500	731.9	608.04	225	30.81	0	0
Mix5	RA20-NS0	20	0	500	731.9	540.48	225	61.62	0	0
Mix6	RA30-NS0	30	0	500	731.9	472.92	225	92.42	0	0
Mix7	RA10-NS1.5	10	1.5	492.5	731.9	608.04	225	30.81	7.5	0
Mix8	RA20-NS1.5	20	1.5	492.5	731.9	540.48	225	61.62	7.5	2.5
Mix9	RA30-NS1.5	30	1.5	492.5	731.9	472.92	225	92.42	7.5	3.75
Mix10	RA10-NS3	10	3	485	731.9	608.04	225	30.81	15	2.5
Mix11	RA20-NS3	20	3	485	731.9	540.48	225	61.62	15	3.75
Mix12	RA30-NS3	30	3	485	731.9	472.92	225	92.42	15	2.5
Mix13	RB10-NS0	10	0	500	731.9	608.04	225	32.9	0	3.75
Mix14	RB20-NS0	20	0	500	731.9	540.48	225	65.8	0	2.5
Mix15	RB30-NS0	30	0	500	731.9	472.92	225	98.71	0	3.75
Mix16	RB10-NS1.5	10	1.5	492.5	731.9	608.04	225	32.9	7.5	2.5
Mix17	RB20-NS1.5	20	1.5	492.5	731.9	540.48	225	65.8	7.5	3.75
Mix18	RB30-NS1.5	30	1.5	492.5	731.9	472.92	225	98.71	7.5	2.5
Mix19	RB10-NS3	10	3	485	731.9	608.04	225	32.9	15	3.75
Mix20	RB20-NS3	20	3	485	731.9	540.48	225	65.8	15	2.5
Mix21	RB30-NS3	30	3	485	731.9	472.92	225	98.71	15	3.75

Note: R: rubber, NS: nano silica, C: cement, CA: coarse aggregate, FA: fine aggregate W: water, SP: superplastisiser.

EXPERIMENTAL RESULTS AND DISCUSSION

Workability

The standard slump test according to ASTM C143/ C143-13 [25] was conducted to measure the workability of fresh concrete for all mixtures. Figures (2) and (3) show the effect of increasing rubber content on the workability of concrete with and without nano-silica for both sizes of rubber, RA and RB. Generally, increasing the percentage of rubber had a negative effect on the workability of the mixes, regardless of the rubber particle size. There is a decrease in the slump by 3.13%, 10% and 13.13% and about 15.63%, 21.3% and 28.13% for 10%, 20%, and 30% RA and RB, respectively, in comparison to control mixtures. This reduction is attributed to the higher water absorption of rubber compared to fine aggregate, which decreases the free water, leading to less workability of all rubberised mixtures. However, although the reduction in slump was noticed during mixing and casting, the increased amount of rubber still produced a workable mix compared to the control mix.

Furthermore, it was discovered that the larger the rubber particle size, the greater the reduction in slump values.The slump of mix with 30% RB was recorded as 115 mm, while the slump of concrete with 30% RA was 136 mm due to the higher water absorption of RB compared to RA. Thus, the saturated surface dry water absorption of RB is 5.97%, which is higher than RA (4.56%). This implies that the larger particles of rubber will absorb more water during the mixing, than the finer particles of rubber to reach the saturated, surface dry condition.

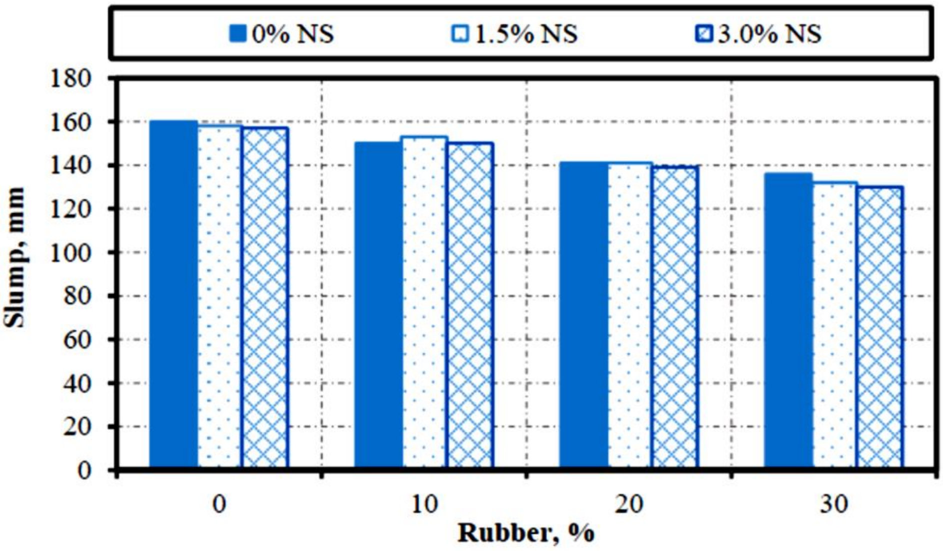


Figure 2: Slump of rubberised concrete with and without NS, RA

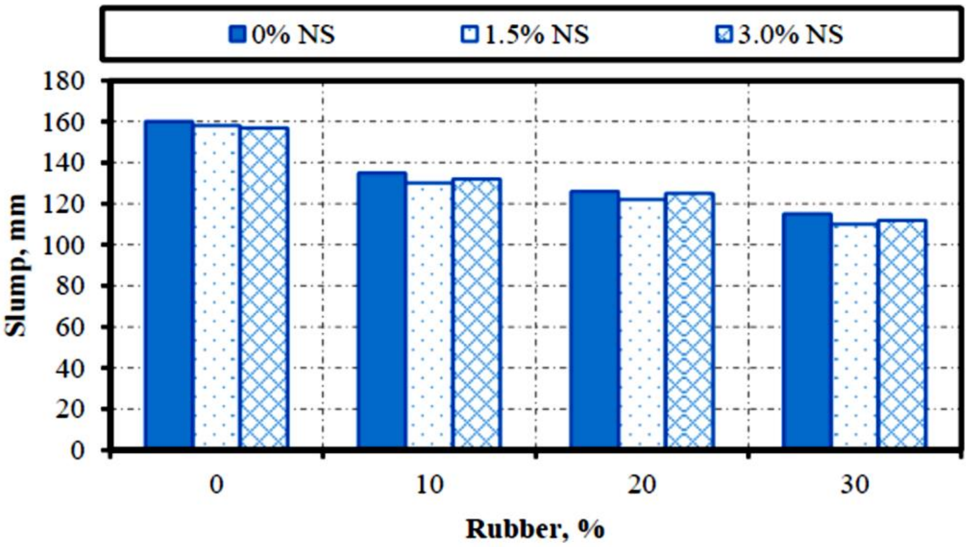


Figure 3: Slump of rubberised concrete with and without NS, RB

The addition of nano-silica to rubberised concrete mixes resulted in an increase in water demand. This is principally due to the large specific surface area of the nanoparticles. Thus, the cement paste workability resulted in being significantly lower than expected due to the interactions between nano silica and the cement paste. To maintain a consistent level of workability for the rubberised concrete mixtures with nano silica, several trial batches were performed to adjust the dosages of superplasticizer. In general, rubberised concrete batches with and without nano-silica exhibited reasonable workability in regards to simplicity of handling, placement, and finishing.

Dry density

The hardened concrete density was determined in accordance with BS 1881-114 [26]. The density of concrete mixtures was expected to be reduced by the addition of rubber, as the density of rubber is less than that of fine aggregate. Figure (4) shows that the inclusion of either RA or RB resulted in a decrease in concrete density. It can be seen that concrete with RA exhibited a lower density than that with RB, and as the rubber level increases in the mix, the density decreases, in line with the original density values of the rubber particles, where RB has a slightly higher density (776 kg/m3) than RA (726.5 kg/m3). The density decreased from 2400 kg/m3 for the control mix to 2179 kg/m3 and 2197 kg/m3 which is about 9.2% and 8.4% with respect to the control mixtures when 30% of the sand was replaced by RA and RB, respectively. The density decreased by about 3% when the percentage of rubber inclusion increased from 10 to 20% and 20 to 30%. This trend was observed in all mixtures, similar to that observed in previous studies [27, 28].

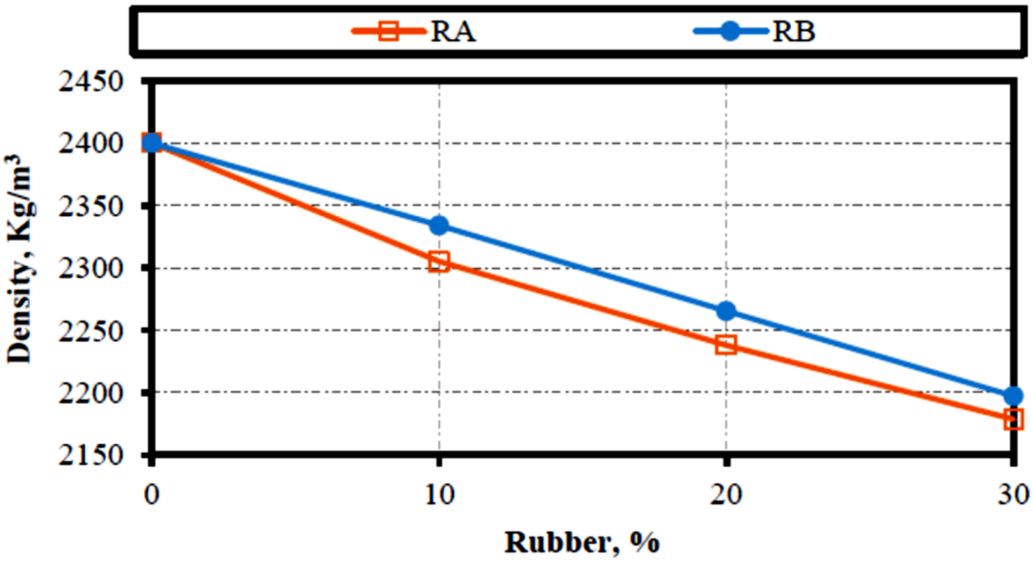


Figure 4: Density of rubberised concrete

Figure (5) shows that the addition of NS to rubberised concrete mixtures generally increases the density compared to rubberised concrete (RuC) mixtures without NS owing to the ability of nano silica to fill the pore structure, making the concrete mixtures more compact and denser. The density of RuC with 10%, 20% and 30% replacement of RA increases by 0.11%, 0.42%, and 0.85% respectively, on 1.5% replacement of cement by nano silica. However, the density of rubberised concrete with 10%, 20% and 30% replacement of RB increased by 0.22%, 0.58% and 0.68% respectively, on 1.5% replacement of cement by NS.

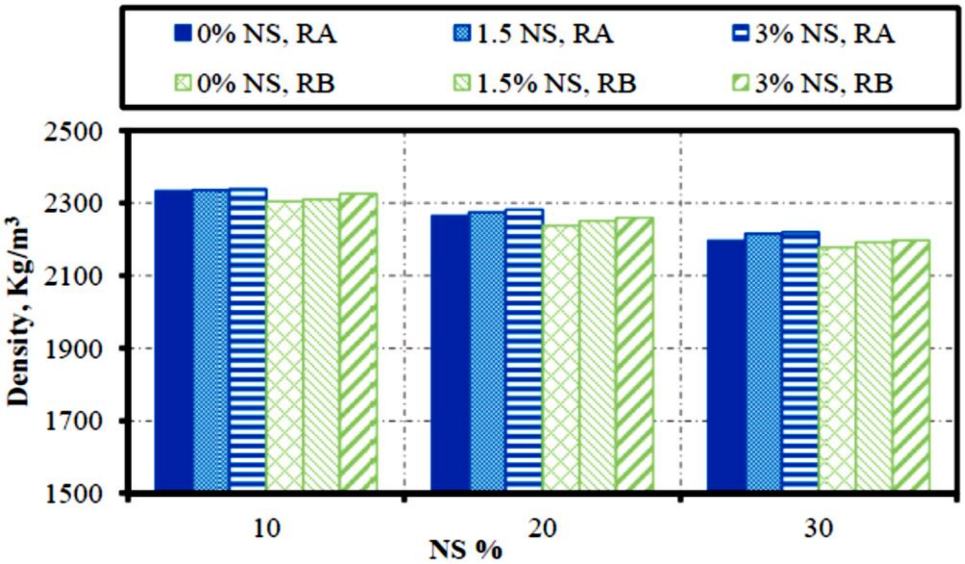


Figure 5: Density of rubberised concrete with NS.

Absorption of water

After 28 days of curing, three cubes of each mixture were taken out of the water tank for a water absorption test according to BS 1881-122 [29]. Figure (6) shows the variation of water absorption results of concrete for two different sizes of rubber with and without the addition of NS. As expected, the increase in the rubber percentage leads to an increase in water absorption. However, the partial replacement of cement by nano silica leads to a decrease in water absorption. It was observed from Figure (6) that 10%, 20% and 30% rubber replacement increased the water absorption by 14%, 26%, and 37.6%, and around 19%, 26%, and 61.9%, for RA and RB respectively, in comparison with the control mix. It was also observed that the water absorption of rubberised concrete decreased with increasing dosage of NS. This phenomenon was due to the denser packing of the particles present in the mixture and also due to the pozzolanic activity of the nano-silica , which filled the voids between cement grains, reducing the water absorption of mixtures.

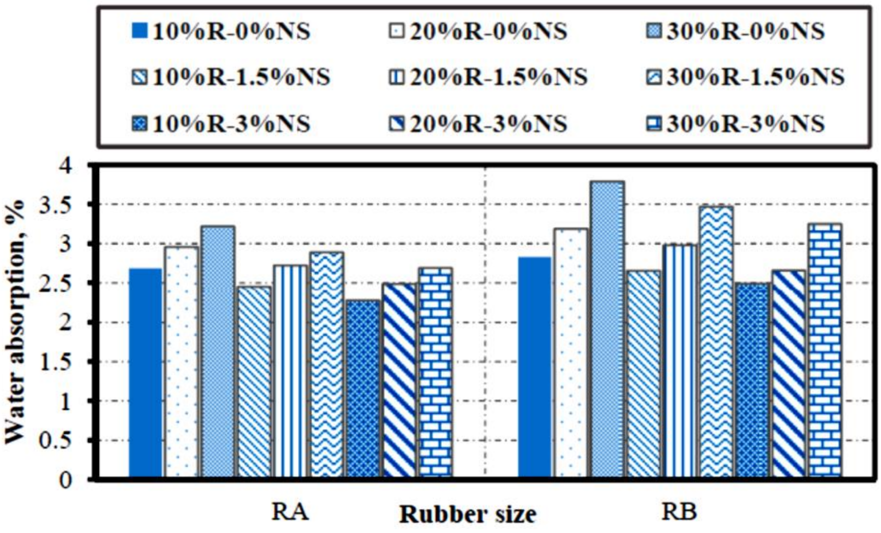


Figure 6: Water absorption of concrete with two different sizes of rubber.

Porosity

Porosity is defined as the volume of pores to the total volume of the sample ratio. A simple method to measure the material porosity is the vacuum-saturation method. The test was carried out on three samples of each mixture. Firstly, the samples were dried at 100 ±5°C for around 24 h, until a constant weight was achieved, then their weight was recorded. The dried samples were submerged underwater in a vacuum vessel for 2 hours, and then these samples were kept in water for an extra 24 hours to ensure full water saturation. After wiping out the wet surfaces of the specimen with a dry cloth, the weight of the sample is recorded. The ratio of the weight difference before and after soaking in water divided by the concrete volume is considered as porosity.

The variation in porosity of concrete made with different mixtures containing rubber and NS is shown in Figure (7). It can be seen that there was an increase in concrete porosity with the increase of rubber content for the two sizes of rubber. With 30% RA, the porosity is 7.05%, whereas samples with RB had a porosity of 8.35% or almost 1.5 times higher compared to control concrete. The increased void content of rubberised concrete is attributed to the tendency of rubber to float in mixtures, which makes the compaction of rubberised concrete specimens difficult and ineffective. Thus, the void percentage in rubberised concrete mixtures increased with the increase of rubber content and therefore the retention of water in those voids during the period of curing.

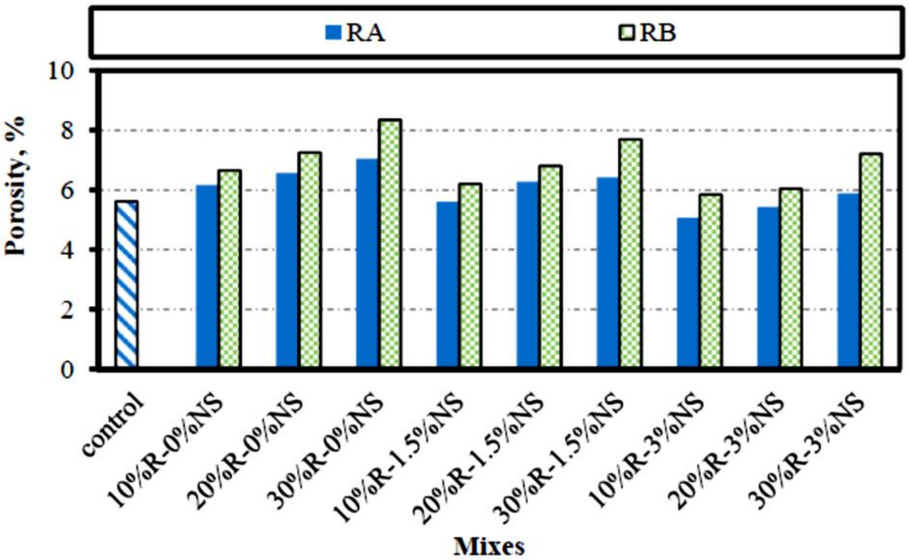


Figure 7: Porosity of different mixes of rubberised concrete mixes

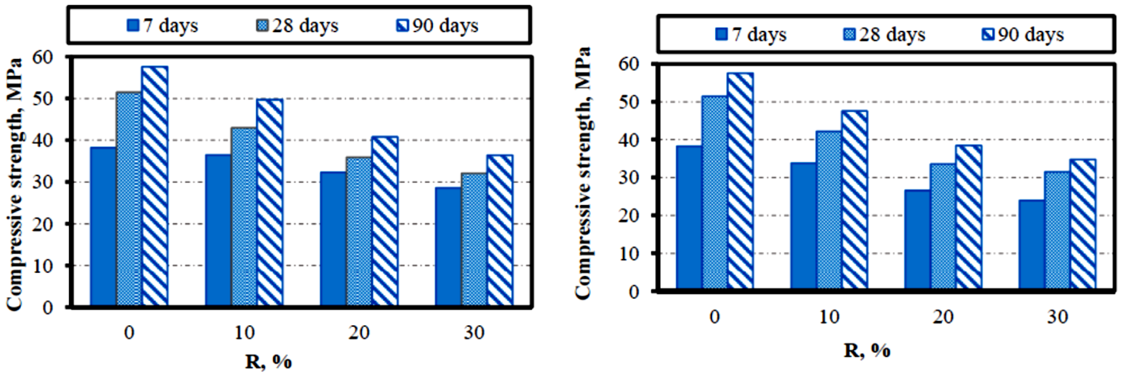
Compressive strength

The compressive strength of each concrete mix was obtained at the ages of 7, 28 and 90 days by testing three cubes of size 100×100×100 mm in accordance with BS EN12390-3:2009 [30]. The average of three samples' results was taken as the final result of concrete's compressive strength. The effect of various ingredients on concrete's compressive strength is discussed below.

Effect of rubber content

Figure (8) shows the effect of replacing the fine aggregate with crumb rubber on compressive strength at 7, 28 and 90 days: Figure (8a) for RA and Figure (8b) for RB. It can be seen that the RB replacement causes a larger reduction in strength than the RA replacement for all mixtures. The reduction in rubberised concrete mixtures as compared to control mixes was 25.3%, 37.6% and 36.8% for 30% replacement of fine aggregate by

RA, and 37.4%, 38.8% and 39.6% for 30%RB replacement at 7, 28 and 90 days, respectively. These results indicate that rubberised concrete mixed with smaller size of rubber particles yields a lower reduction in compressive strength due to the void-filling ability of finer rubber particles, which causes less void space. Moreover, it can be clearly observed that the compressive strength reduces with a higher replacement level of rubber regardless of the size of the rubber. This reduction in compressive strength can be referred to as the low stiffness of rubber particles that caused weak bonding between rubber particles and cement paste, which led to a decrease in the compressive strength. A similar trend of strength reduction with the use of various rubber sizes in concrete was reported by Haolin et.al, (2015).



(a) (b)

Figure 8: Effect of rubber replacement on compressive strength of the tested mixtures at 7 and 28 day (a) RA, and (b) RB.

Effect of nano-silica replacement

The effect of different NS contents on the 7, 28 and 90 days compressive strengths of rubberised concrete mixtures is shown in Figures (9), (10) and (11), respectively. It was observed that the partial replacement of cement with NS significantly improved the rubberised concrete performance. The addition of 1.5% NS was successful in achieving a higher compressive strength at 7, 28 and 90 days for mixes with 10% RA as a fine aggregate replacement than the control mix. For higher rubber content, nano-silica partially alleviated the loss in strength.

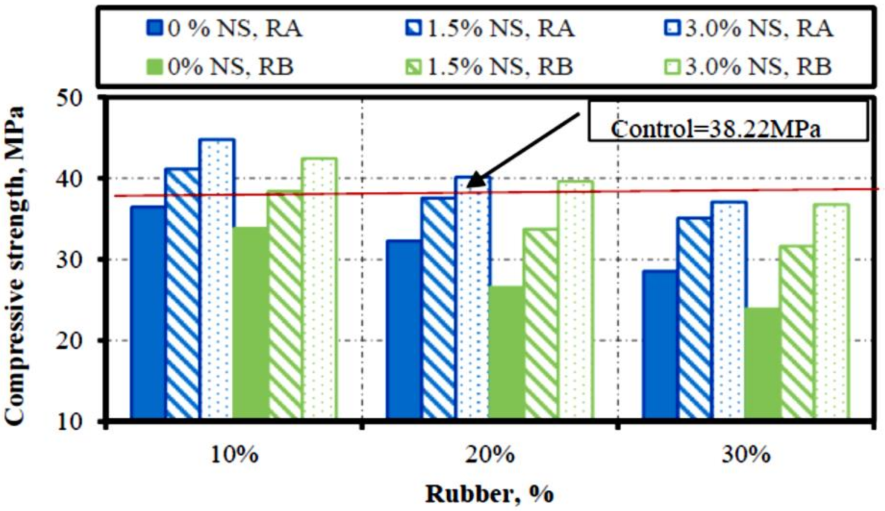


Figure 9: 7 days compressive strength of rubberised concrete

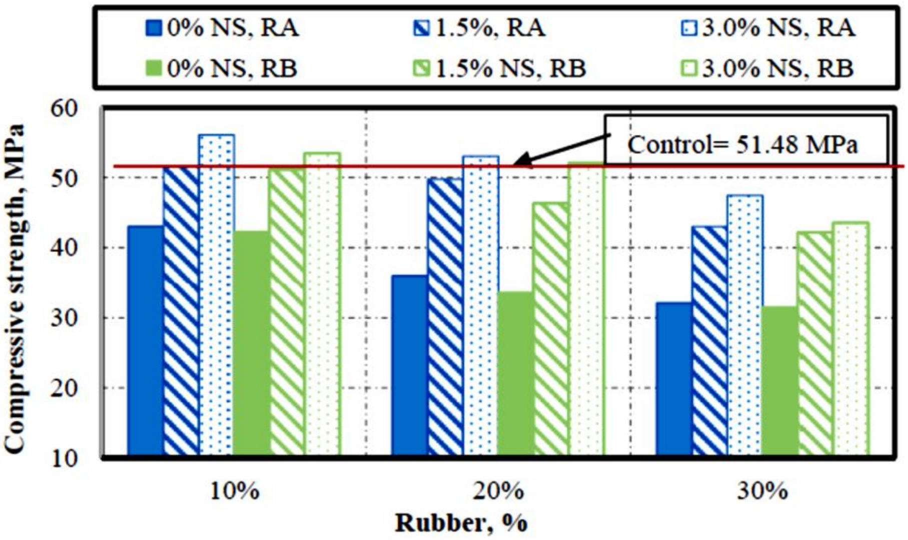


Figure 10: 28 days compressive strength of rubberised concrete

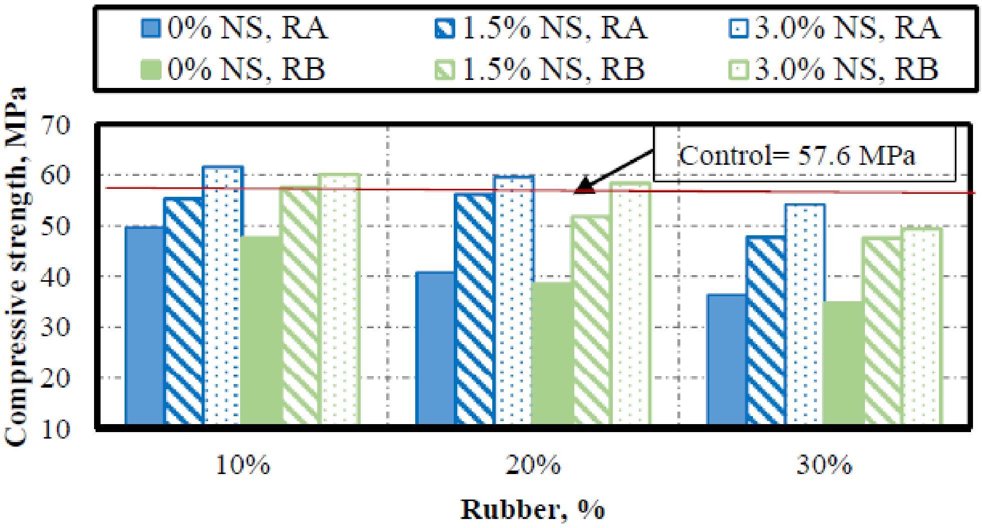


Figure 11: 90 days compressive strength of rubberised concrete

This increase in compressive strength with nano silica might be due to the ability of nano silica in refining the pores and improving hydration products distribution, especially at interfacial transition zone (ITZ) leading to better adhesion between rubber and cement matrix as observed in previous investigations [31, 32].

Figure (12) presents the enhancement of compressive strength as the nano-silica level increased from 0% to 3% while the percentage of rubber remained constant at 20% for all mixes. It can be observed that there is an increment in the compressive strength of rubberised concrete as the amount of NS increases. Incorporating 1.5% of NS into the rubberised concrete mixture results in enhancing the compressive strength remarkably by 38.25% and 32.75% for RA and RB, respectively, compared to the control mix (NS 0%). This is mainly due to the advantages of NS in the rubberised concrete mixes, as aforementioned. A small improvement in the compressive strength of rubberised concrete can be observed with the increase in nano-silica level from 1.5% to 3.0%. Mohammed and Awang [33] attributed this condition to an inadequate amount of NS to fully react with the free portlandite.

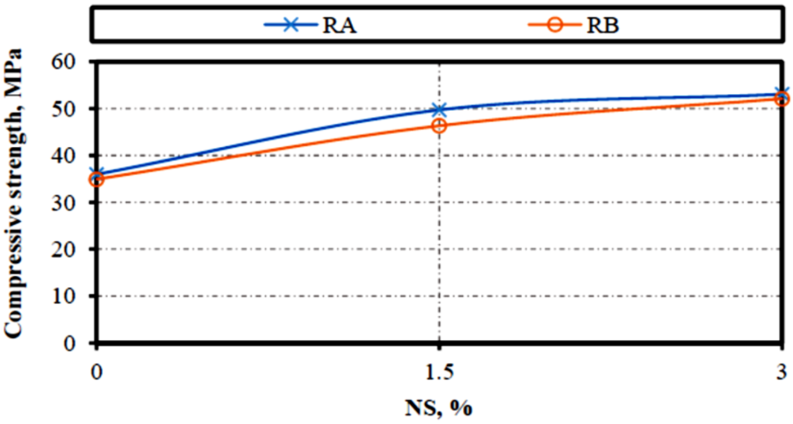


Figure 12: Compressive strength versus nano silica addition for rubberised concrete mixture with 20% rubber.

Figures (13) and (14) seem to show a strong correlation between compressive strength and both density and porosity, respectively, for all mixes. It can be clearly observed that the decrease in the density of concrete mixes is linked with the reduction of their compressive strength. Additionally, it should be noted that the increment of rubber content in concrete lowers its density, regardless of the size of the rubber. However, the compressive strength has an inverse correlation with porosity, consistent with findings in [34-36].

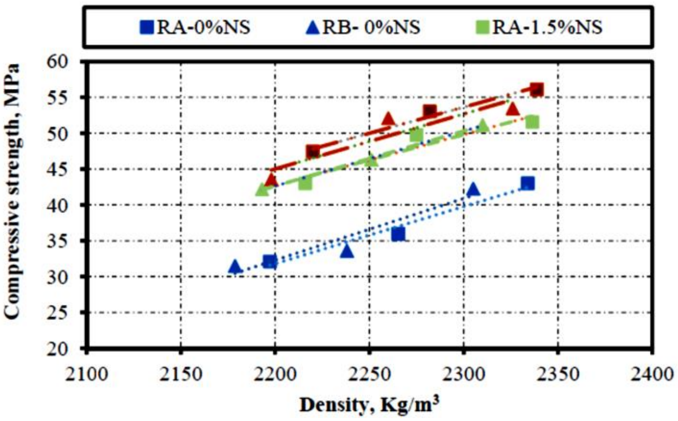


Figure 13: The relationship between Density and compressive strength of rubberised concrete

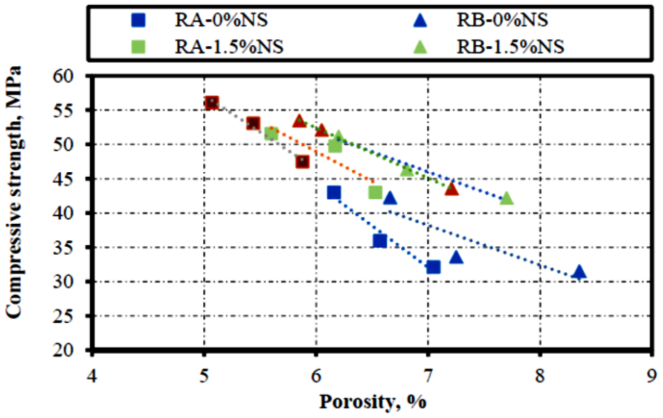
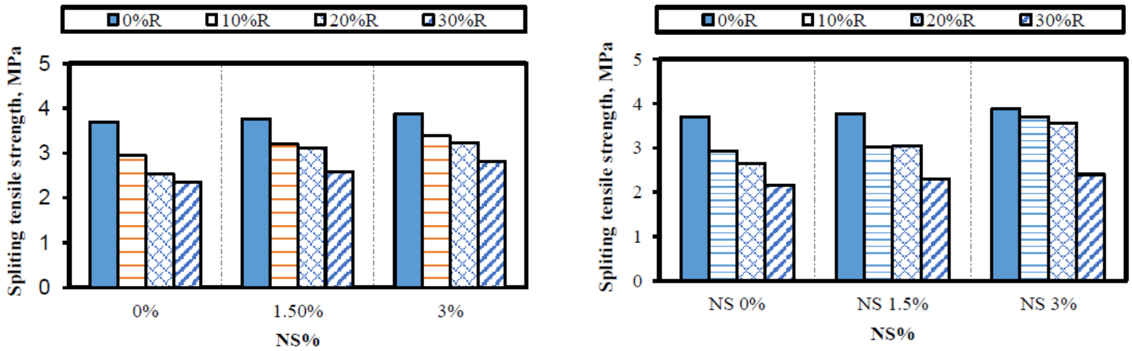


Figure 14: The relationship between porosity and compressive strength of rubberised concrete

Splitting tensile strength

The splitting tensile strength of various concrete mixes is obtained by testing 150 mm x 300 mm concrete cylinders in accordance with BS 1881-117 [37]. The average of three samples results was taken as the final result of the concrete splitting tensile strength. All the results of splitting tensile strength tests are presented in Figure (15). The strength reduction trend for the splitting tensile strength is similar to that observed in the compressive strength. Control the concrete mix had an initial splitting tensile strength of 3.7 MPa. Clearly, this initial strength value dropped to 2.35 MPa and 2.15 MPa when 30% of the fine aggregate was replaced by RA and RB, respectively. However, the splitting tensile strength of rubberised concrete is enhanced as the amount of nano silica has been increased. Adding 3% of NS to rubberised concrete mixture with 20% replacement leads to increasing the splitting tensile strength by 27.36% and 34.86% when using RA and RB, respectively. This improvement in the splitting tensile strength is attributed to the high pozzolanic activity of the nano-silica in cement.



(a) (b)

Figure 15: Variation in the splitting tensile strength of rubberised concrete with nano silica, (a) RA and (b) RB.

Flexural strength

A flexural strength test of hardened concrete was carried out at 28 days of curing using a 100 × 100 × 500 mm prism sample in accordance with ASTM C78/78M-15 [38]. The average value of two prisms for each mix was recorded. The results of flexural strength for rubberised concrete are shown in Figures (16a) for RA and (16b) for RB. It can be seen that, as in the case of compressive strength and splitting tensile strength, the addition of rubber aggregates decreases the flexural strength. This reduction was less than 14% for both sizes of 10% rubber replacement. However, when 20% and 30% of the fine aggregate were replaced with RA, there was a decrease in flexural strength of approximately 17.7% and 28.9%, respectively. In a similar trend, there was a higher reduction of around 23% and 33.9% when using RB.

It can be concluded that the smaller the particle size of rubber, the higher the strength due to the higher filler ability of the smaller rubber size, in increasing the density of concrete and reducing the probability of fracture. The decrease in flexural strength with the increase in rubber content was in agreement with the findings of previous studies [11, 39, 40]. However, others reported an increase in flexural strength [33, 41].

The results of the addition of NS showed an enhancement in flexural strength compared to the mixes with 0% NS as presented in Figures (16a) and (16b). This was expected due to the ability of nano silica to fill the voids, thus providing a good adherence between the rubber particles and the cement paste.

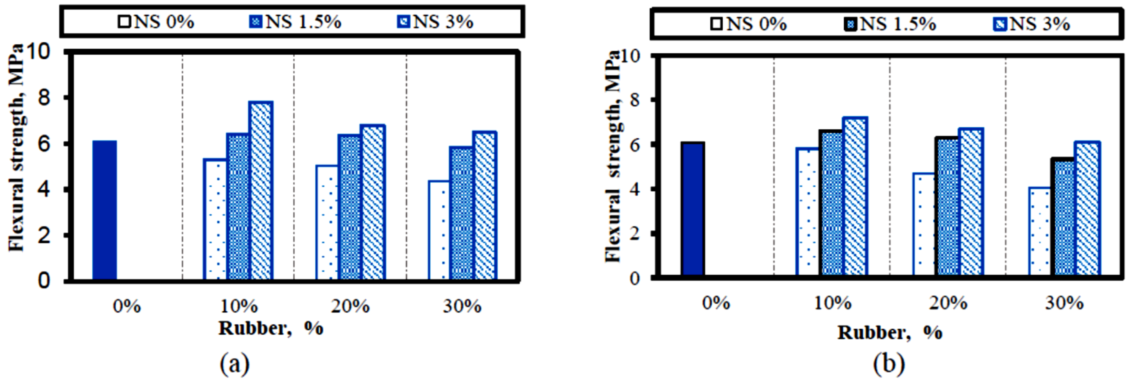


Figure 16: Flexural strength for various rubber percentages, (a) RA and (b) RB.

Drying shrinkage

Drying shrinkage can be defined as a reduction of concrete volume due to an overall loss of water from cement paste to the environment through evaporation. Drying shrinkage was experimentally investigated over 90 days based on ASTM C157/08 [42], using prisms with dimensions of 100x100x300 mm. Figures (17) and (18) illustrate the free drying shrinkage curves of concrete incorporating different dosages of rubber and NS. The drying shrinkage strains for control concrete and rubberised concrete at 90 days range between 520 and 684 microstrain. It can be seen that the addition of rubber in to concrete increases the drying shrinkage strain in relation to the rubber replacement level and the control mix proportions. This increment of drying shrinkage can be attributed to the deformation property of rubber, which decreases the internal restraints for drying stresses, which leads to an increase in the drying shrinkage and also may be due to an increase in the porosity of rubberised concrete. It is observed that the drying shrinkage strain for concrete with RA and RB was slightly similar at the very early ages, whereas there was a considerable change after 28 days. A similar trend has been observed by [27, 40, 43]. The effect of NS content on drying shrinkage strains and the variations with time for concrete with RA and RB are also presented in Figure (17) and Figure (18). It can be seen that the addition of NS caused a reduction in drying shrinkage strain compared to rubberised concrete mixtures. This reduction is due to a decrease in porosity compared to rubberised concrete.

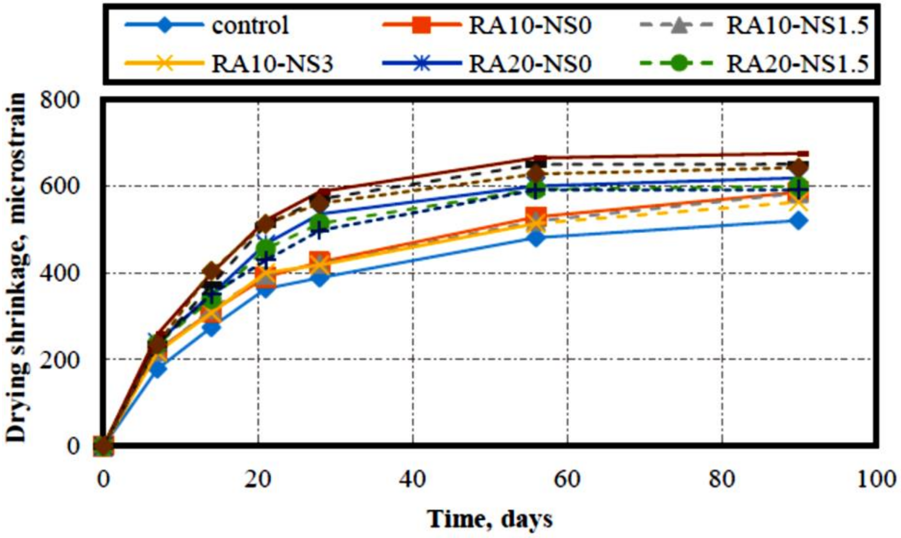


Figure 17: The effect of RA content and NS addition on concrete drying shrinkage.

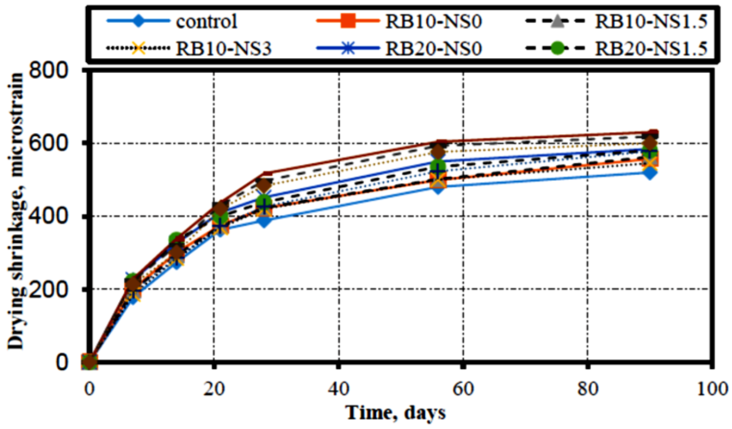


Figure 18: The effect of RB content and NS addition on concrete drying shrinkage.

Figure (19) illustrates the relationship between rubber content and drying shrinkage strain. There is almost a linear relationship between rubber content and drying shrinkage strain with $R^2 = 0.9849$ and 0.99903 for concrete with both different sizes of RA and RB, respectively, indicating a positive correlation for both sizes of rubber. However, Figure (20) shows an inverse correlation between drying shrinkage and nano silica content for both RA and RB concrete mixes, based on the experimental results of this study.

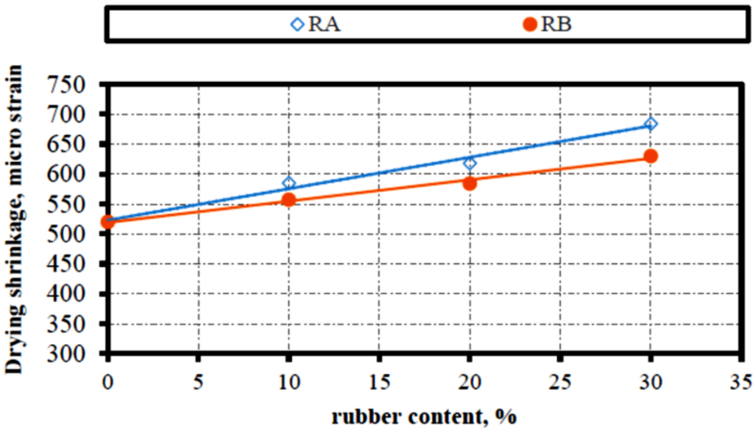


Figure 19: Relation between rubber content and drying shrinkage at 90 days for two different sizes of rubber.

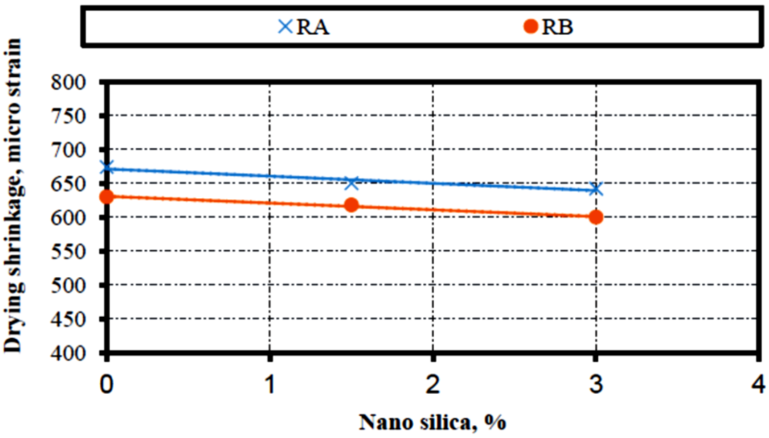


Figure 20: Relation between nano silica content and drying shrinkage at 90 days for two different sizes of rubber.

CONCLUSIONS

A series of tests were conducted on concrete mixes to evaluate the workability and mechanical properties of rubberised concrete incorporating colloidal nano silica. Based on the experimental test results of this study, the following conclusions can be summarised:

- The use of different particle sizes of rubber in concrete as a replacement for fine aggregates affects the workability. The reduction in slump values was observed as the rubber particle size was increased. This is due to the fact that the water absorption of the larger particle size of rubber is higher than the finer rubber particles.
- The addition of rubber aggregate significantly decreased the density whilst increasing the porosity and water absorption. The reduction in density is mainly due to the low specific gravity of rubber. Concrete mixes prepared with the smaller size of rubber particles show a higher increase in water absorption and porosity compared to those with larger ones. On the contrary, concrete with the larger rubber particles has a lower density value than those with the finer rubber particles.
- The compressive strength, splitting tensile strength and flexural strength decreased with the increase of both rubber content and rubber size. However, the addition of variable dosages of NS showed a remarkable enhancement in the strength of rubberised concrete.
- The results of drying shrinkage tests revealed that incorporating rubber into concrete resulted in a higher free drying shrinkage strain. However, incorporating NS into rubberised concrete decreases the drying shrinkage strain.

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