Proc. 1st International Conference on Structural Engineering Research (iCSER 2017)
20-22 Nov 2017, Sydney, Australia
ISBN: 978-0-6480147-6-8

Shear Response of Concrete with Nano-Materials

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Abstract

Concrete exhibits excellent compression strength and durability properties; however, it is weaker in shear. The shear resistance of concrete is largely influenced by the strength of the interfacial zone between the aggregates and the mortar. To enhance the density and strength of the interfacial zone of the concrete, silica fumes have been mixed with the mortar and aggregates. This investigation focuses on the effect of multi-walled carbon nano-tubes (MWCNTs) and graphite nano-fibres (GNFs) on the shear strength of concrete. Since these nano-materials are small in size and possesses large surface areas and strong van der Waals interaction forces, it is expected that they can bridge the zone between the mortar and aggregate interface, thus limiting the formation and growth of micro-cracks. However, nano-materials tend to bundle up and form entangled clumps due to their strong van der Waals interaction forces. For this reason, the nano-materials were dispersed using gum arabic (GA). Two series were investigated; one incorporating GA and MWCNTs, and the other one incorporating GA and GNFs. In both series GA equivalent to 1% of the water was mixed with water and nano-materials (MWCNTs or GNFs) equivalent to 1% of the cement weight were mixed with the cement powder and subsequently mixed with the aggregates.

Keywords: Concrete, Nanomaterials, Shear strength, Graphite nano-fibres, Multi-walled carbon nano-tubes, Gum arabic, Functionalisation.

1. INTRODUCTION

Concrete is a heterogeneous material, consisting of different types of material (aggregates, hardened cement paste and aggregate-paste interface (interfacial transition zone)), which have different properties. This means that when concrete is loaded, the internal stresses and strains are not uniform; they are concentrated in certain areas. The aggregates are the strongest and least likely material to fail in the concrete, the hardened cement paste contributes greatly to the strength of concrete and is dependent on the porosity and the microstructure of the hardened cement paste, and the aggregate-paste interface (interfacial transition zone) is generally the weakest link in concrete. If concrete fails it is most likely that the interfacial transition zone will fail first, followed by the hardened cement paste. Failure of aggregate in concrete is very rare and is only encountered in high strength concrete applications or when inferior materials are used. The interfacial transition zone has a lower mechanical strength and a higher permeability than the rest of the surrounding concrete. It is unclear as to where the zone ends, and how thick it is, since it gradually blends into the surrounding concrete matrix. Decreasing the porosity of this zone will result in concrete having higher shear strength. The purpose of this investigation is to evaluate the influence of graphite nano-fibres and carbon nano-tubes on the shear strength of concrete, and to find out whether the properties of concrete could be enhanced so as to minimize the amount of shear reinforcement steel used in reinforced concrete structures. Silica fumes have been successfully used to increase the density and strength of the interfacial zone of the concrete. It is expected that the addition of carbon nano-tubes, which are much finer than silica fumes, could increase the strength of the interfacial transition zone of the concrete, and subsequently the overall strength of concrete, much more than silica fumes. In general the shear strength of concrete is approximately 50% of the compressive strength [1, 2].

1.1 Graphite nano-fibres (GNF)

Graphite nano-fibres (GNFs) are formed from carbon atoms, which are arranged in a hexagonal or honeycomb pattern as sheets and stacked one above the other. A single sheet is extremely strong, flexible, and stable, however, it is weakly bonded to neighbouring sheets of graphite [3]. GNFs consist entirely of sp^2 bonds [4]. Further, GNFs have diameters ranging from 1 – 2 nm and a length-to-diameter ratio exceeding 10 000, and are the strongest composites known to man (approximately three hundred times stronger than steel). Problems inhibiting the use of GNFs in the concrete mix are the tendency of the GNFs to stick together and form balls due to Van der Waals forces, the lack of cohesion between the GNFs and the concrete materials, the lack of reliable large scale production and the expensive cost of producing the GNFs. Cohesion between the GNFs and the concrete materials can be increased by the use of GA. A process called functionalization is used to aid in both the dispersion and the purification of the GNF.

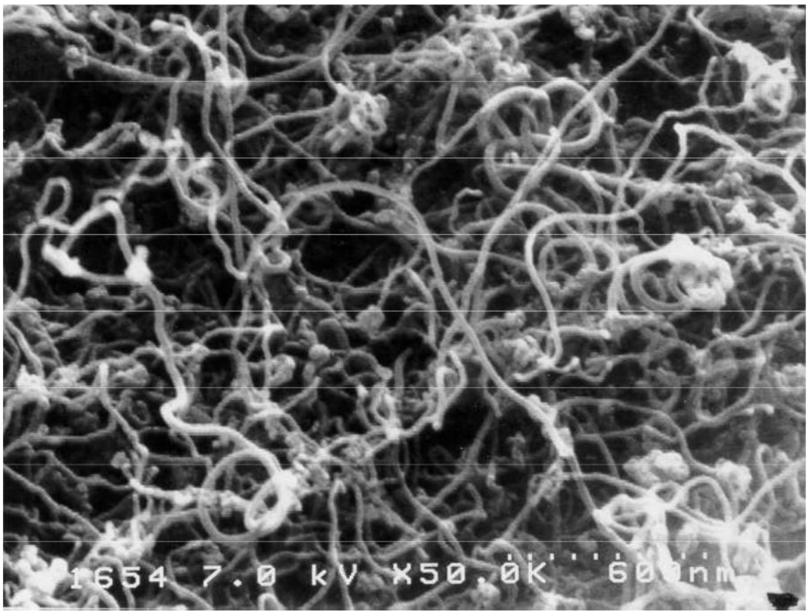


Figure 1 Graphite nano-fibres from a Scanning Electron Microscope [5]

1.2 Carbon nano-tubes

Carbon nano-tubes (CNTs) are allotropes of carbon, and are found as single-walled and multi-walled nano-tubes. A single-walled carbon nanotube (SWCNT) is a single layer or sheet of graphite, rolled into a long, thin seamless cylindrical tube of 1 – 2 nm diameter and has a length-to-diameter ratio exceeding 10 000 [4], as shown in Figure 2, while multi-walled carbon nano-tubes (MWCNTs) are cylindrical tubes made up of several layers of graphite sheets [6]. Unlike natural carbon nano-tubes, man-made nano-tubes are closed at both ends [7]. The mechanical properties of CNTs are astounding, but are still not yet fully standardised, because of the difficulty encountered in performing tests on the CNTs at nano-scale. Like GNFs, CNTs are composed entirely of sp^2-hybridized C-C covalent bonds and have approximately the same mechanical properties as GNFs. These are stronger than the sp^3 bonds found in diamond [8]. Carbon nano-tubes have been reported to have attained a strength of 150 GPa [6], and although mixed reports exist about the exact strength of CNTs, all agree it is far much than the strongest forms of steel available. Although carbon nano-tubes have extremely high tensile strength (150 GPa) and Young’s modulus (1054GPa), their strength under compression, torsion and bending is poor due to their hollow structure and high aspect ratio (ratio between the longer dimension (length) and shorter diameter. Carbon nano-tubes are highly flexible and do not just fracture, but rather form kink-like ridges.

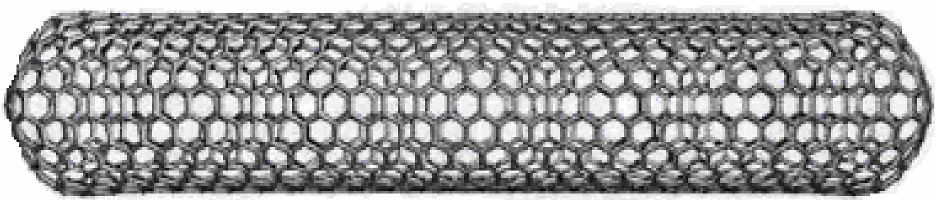
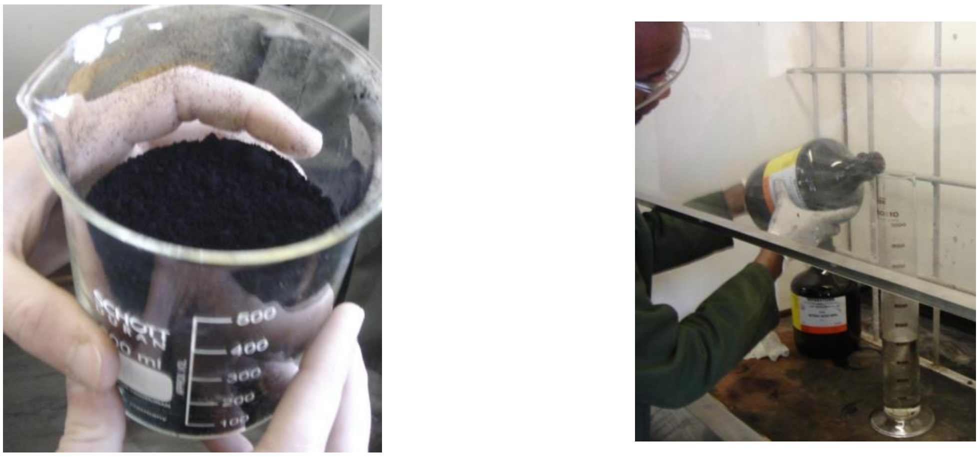


Figure 2: Closed single-walled carbon nano-tube [8].

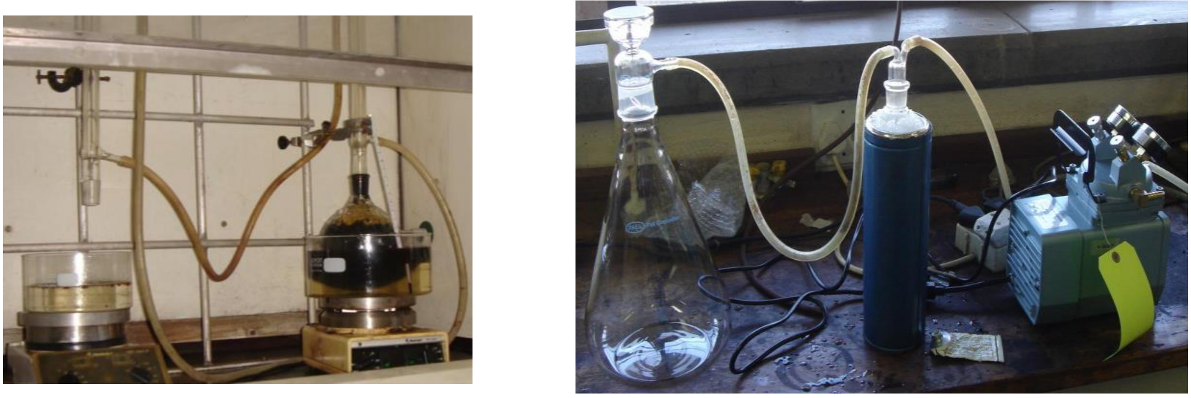
2.0 Experimental procedure

2.1 Functionalization of GNFs and MWCNTs

As indicated before, in order to remove any impurities from GNFs, and to help in the dispersion of these nano-fibres, a process called functionalization was used. Impurities in graphite nano-fibres can potentially decrease the strength of the nano-fibres by up to 85%. Although MWCNTs are supplied clean, the cohesion between the MWCNTs and the concrete matrix still needs to be increased by functionalization (attaching carboxylic acid groups to the MWCNTs). Functionalization also assists in dispersing the MWCNTs through the concrete mix. Lack of cohesion between the CNTs and the concrete matrix results in “fibre pull-out” and sliding between the matrix and the CNTs at relatively low loads and thus do not allow the composite to reach high strengths [9]. It has been suggested that weak CNT-matrix cohesion results from the smooth surfaces and small diameter of CNTs. Currently there are two ways to resolve this problem, either by functionalising the CNTs or the aggregate particles [8].



(a) GNFs (b) Mixing of the acids



(c) Refluxing of the nano-materials (d) Filtering process

Figure 3 Functionalization process

To accomplish the functionalization process, the GNFs/MWCNTs were weighed and dissolved in an 80 ml acid mixture, containing a 3:1 ratio of sulphuric acid to nitric acid. In CNTs, a mixture of sulphuric acid and nitric acid is used to covalently attach carboxylic acid groups on the walls and ends of the MWCNT. The solution was refluxed at 55°C for 24 hours inside the fume cupboard, and left to cool down to room temperature. Functionalized GNFs/MWCNTs of 10-20 grammes were then placed in 2.5 litres of distilled water. The nano-materials were filtered using a 125 nm standard/normal filter paper, washed with more distilled water until the pH was in the range of 5-7, which gave the nano-materilas a neutral acidity. Figure 3 shows the functionalization process. Finally, the acid treated graphite nano-materilas were dried using the pump vacuum. They were then kept dry and sealed until used.

2.2 Casting of concrete cubes

The method of casting concrete followed the usually procedures of preparing concrete cubes. This included, creating the mix design, batching the concrete, checking the slump, casting the concrete in the moulds, curing after 24 hours and testing of the concrete specimens after 28 days. The concrete mix design was performed using the C & CI method [10]. Three different concrete test samples were mixed in each series; the first sample were merely a standard reference concrete mix, with nothing added to the mix, the second concrete mix included a soluble solution of GA, and the third and last batch included functionalized GNFs/MWCNTs and GA. The third test was the core part of this investigation. GA was mixed with water and added to the specimens to help improve the cohesion between the cement paste and the GNFs. Since GA had a tendency of decreasing the concrete strength and increasing the workability, the water cement ratio was adjusted from 0.73:1 to 5:1. The amount of GA and water was added to the concrete nano-material mix using in-situ trial concrete mixes. The nano-materials were functionalized, mixed directly with the cement powder, and subsequently added to the aggregate. The process of functionalization leaves nano-materials in flake-like structures. Before mixing the nano-materials with cement, the nano-materials were crushed into fine powder using a mortar and pestle. Safety equipment (goggles, gas masks, and latex gloves) was used to mitigate the health risks posed by crushing the nano-materials. The concrete was then cured as per the guidelines given in SANS 5861-1:2006 [11]. Table 1 provides the mix design used in each of the batches. Slump tests were performed on the three batches prior to filling the moulds. The slump tests were performed as per SANS 5862-1:2006 [12], and the results for the slump tests are also given Table 1.

Table 1 Concrete mix design for each series

Series 1	Materials	Batch 1 – Standard	Batch 2 – Gum Arabic	Batch 3 – Gum Arabic + MWCNTs
	Cement	8.558 kg	8.558 kg	8.558 kg
	Sand (7:3 blend)	23.18 kg	23.18 kg	23.18 kg
	Stone	15.41 kg	15.41 kg	15.41 kg
	Water	6.248 kg/*l*	6.186 kg/*l*	6.186 kg/*l*
	Gum Arabic	-	62.5 m*l*	62.5 m*l*
	MWCNTs	-	-	86 g
	Slump	40 mm	50 mm	10 mm
Series 2	Materials	Batch 1 – Standard	Batch 2 – Gum Arabic	Batch 3 – Gum arabic + Graphite Fibres
	Cement	8.558 kg	8.558 kg	8.558 kg
	Sand (7:3 blend)	23.18 kg	23.18 kg	23.18 kg
	Stone	15.41 kg	15.41 kg	15.41 kg
	Water	6.248 kg/*l*	6.186 kg/*l*	6.186 kg/*l*
	Gum Arabic	-	62.5 m*l*	62.5 m*l*
	Graphite Fibres	-	-	86 g
	Slump	45 mm	55 mm	20 mm

2.2 Shear tests of the concrete

Pure shear stress in concrete is never encountered in practise, as it is always accompanied by the compression and tension, caused by bending. There are no standard methods to determine the shear strength of concrete only. This is due to the fact that it is extremely difficult to set up a test which tests the concrete specimens purely for shear. Attempts have been made in the past to determine the shearing strength of concrete, using concrete beams of very short span. Loads were applied very close to the supports to try and replicate a pure shear scenario. Some of these tests showed the shear strength to be only slightly higher than the tensile strength; others showed it to be 50-90% of the compressive strength [13, 14]. The variation can attributed to the fact that either tensile or compressive stresses may have also been acting on the specimens [13, 14].

A mould in Figure 4, was constructed in order to test the shear strength of the concrete only [15]. Specimens developed from this mould was crushed in the same way as normal concrete cubes, at a standard crushing rate of 100 kN per minute. To achieve pure shear failure, the mould was placed at the centre and aligned vertically in an Avery Davison crushing machine, as shown in Figure 5 (a). The load was applied until the concrete failed in shear. The shear failure plane is illustrated as vertical section between the grooves in Figure 5 (b).

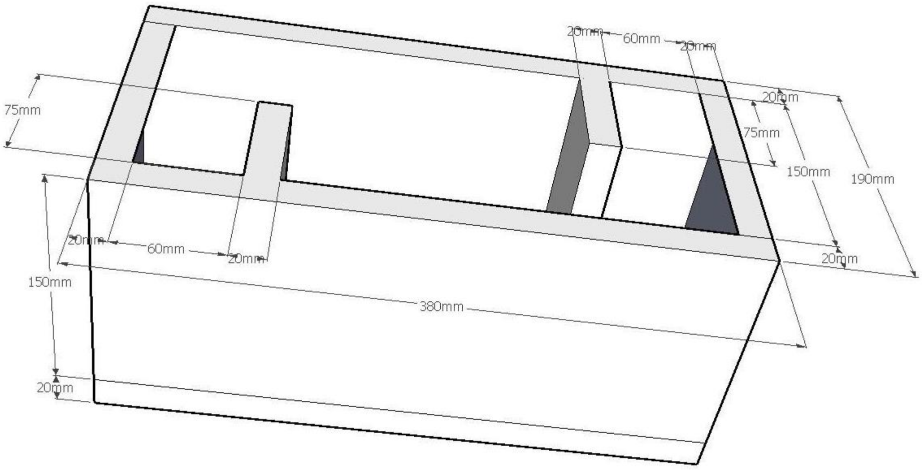


Figure 4: Shear mould dimensions

(a) Test set-up (b) Direct shear failure

Figure 5: Test set-up and shear zone

3.0 Compression results

The results obtained from the experiments are summarized in Table 2, and presented in the form of bar graphs in Figure 6. These graphs show the strength of each sample relative to other samples in the series, and the strength of samples in a series relative to other series. A full statistical analysis of the results was not performed because there are only a few results from each of the different samples. As opposed to the findings in the literature [16], the results show that the addition of GA in both series had a negative effect on the shear strength of concrete. As shown in Series 1 and 2, the results revealed that the addition of GA to the wet concrete decreased the shear strength of concrete by 5 - 6%.

When GA and MWCNTs were added to the wet concrete in Series 1, the strength of the concrete increased by 6%. Although not remarkable, effectively this means that MWCNTs have the potential to increase the strength of concrete by 11 – 12%. This increase may be attributed to the physical, cylindrical shape of the nanomaterials, because they retain a much stiffer and stronger elastic rod due to a rolling process. The addition of the MWCNTs to the concrete results in a loss of workability in the concrete mix as shown in Table 1. However, when both GA and GNFs were added to the wet concrete in Series 2, the strength of the concrete was reduced by 15%. This implies that the addition of GNFS to the wet concrete decreased the shear strength of concrete by a further 9 -10%. The further reduction of the strength may be attributed to the flat shape, and soft and slippery property graphite.

Table 2 Shear strength

Series	Specimen	Control (kN)	GA (kN)	GA + MWCNT/GNFs (kN)
Series 1	S1-1	4.6816	4.1388	4.8091
	S1-2	4.0839	4.0092	4.6688
	S1-3	4.2933	4.2112	4.6326
	Average	4.3529	4.1198	4.6326
	Std Deviation	0.3033	0.1023	0.1972
	CoV	0.0697	0.0248	0.0426
	% Increase/Decrease	0	-5	6
Series 2	S2-1	4.6800	4.2400	4.1600
	S2-2	4.2300	4.0400	3.5700
	S2-3	4.3500	4.2100	3.5800
	Average	4.4200	4.1633	3.7700
	Std Deviation	0.2330	0.1079	0.3378
	CoV	0.0527	0.0259	0.0896
	% Increase/Decrease	0	-6	-15

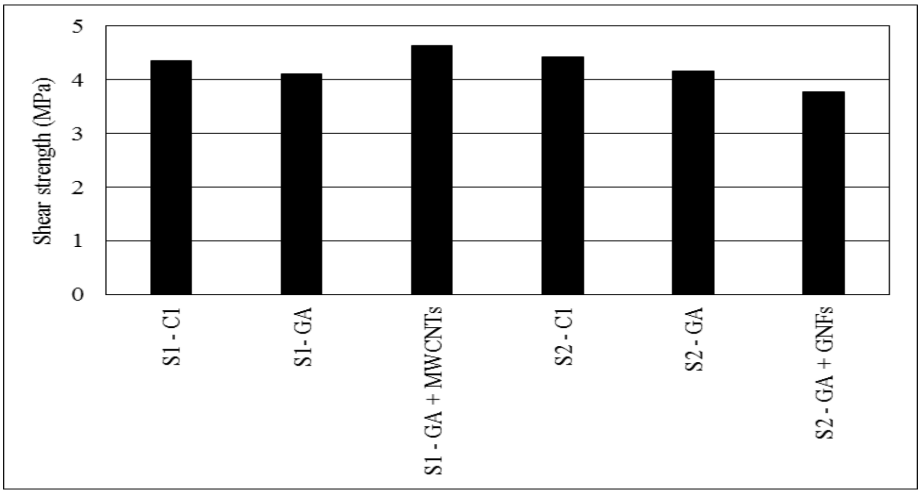


Figure 6 Shear strength of the concrete

4.0 Conclusion

When nano-materials were incorporated into the concrete in a quantity of 1% relative to the cement weight, a shear strength increase was evident. This increase may be attributed to the nano-materials bridging capabilities over the micro-cracks found within the mortar-aggregate interface and nanomaterials physical properties as they are much stiffer and stronger as compared to the softer graphene sheet of GNFs. GNF concrete displayed a decrease in shear strength, due to its soft and slippery properties. On average, the use of GA as a dispersion agent led to decrease in the strengths of concrete. This implies that alternative dispersion techniques should be investigated.

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