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Abrasion and Strength of high percentage Graphene Oxide (GO) Incorporated Concrete

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ABSTRACT: Incorporating Graphene Oxide (GO) in concrete composite has been a good alternative to Pristine Graphene due to its hydrophilic nature and its ability to readily disperse in water the consequent cementitious mix. The addition of GO to the cementitious mix has been found to enhance mechanical properties. This paper aims to assess the abrasion resistance of GO incorporated concrete for its application in road pavement design. Experiments for strength in terms of compression, workability in terms of slump and abrasion resistance in accordance with ASTM-C418-20 using a sand-blasting rig are presented in the paper. It is shown that the addition of GO at percentages between 0% to 0.08% (to cement weight ratio), the compressive strength improves by 39% and 26% at 7 days and 28 days, respectively. The addition of GO consequently affected the workability where it was found that the addition of polycarboxylate ether (PCE) (superplasticisers) can drastically improve the workability, which is essential in practical applications. The abrasion was measured for specimens prepared with a high GO percentage between 0.1% to 0.3% and measured at 7 days and displayed a reduction of 70% of abraded volume at 0.3% GO. Finally, the study presents the benefits of using GO where the reduced amount of cement usage will consequently lead to sustainable concrete construction.

1 INTRODUCTION

The use of Graphene as a Nano-composite material has recently gained traction due to its ability to enhance properties when incorporated into Concrete (Dimov et al., 2018). Literature has shown that properties such as compressive strength, tensile strength and water penetration properties (Shamsaei et al., 2018) are enhanced due to the addition of Graphene, where these have been achieved at usually between 0.01% to 0.08% of Graphene to cement weight ratio (Lin & Du, 2020; Shamsaei et al., 2018).

Like other Carbon-Based Nanomaterials (CBN), such as carbon-nanofibre (CNF) and carbon-nanotubes (CBN), Graphene faces difficulty dispersing due to its hydrophobic nature. This characteristic leads to the poor distribution of particles in the cementitious mix (Zhao et al., 2020). The consequence of poor distribution in the cementitious mix is that it leads to inconsistencies in the structural performance of Graphene-concrete composites. Graphene Oxide (GO), the derivative of Graphene, is a suitable alternative due to its ability to disperse readily due to the existence of functional oxygen groups, making it hydrophilic. However, oxygen functional groups in GO remove "smart" features such as electrical conductivity and thermal conductivity but still retain similar strength enhancements in concrete (Chintalapudi & Pannem, 2020). Thus, the use of GO is the most appropriate and also, the ability to derive from Graphite readily makes it a much more suitable choice, especially where scalability and practical applications are considered.

Concrete road pavements have recently been on an upsurge, especially on major arterial roads where heavy traffic is encountered. Durability, resilience and strength of road pavements have led to longer service life and require less maintenance over time, leading to millions of dollars in annual savings and fewer road closures, thus leading to minimal disruptions to traffic. Thus, the need for more robust and durable roads is of utmost importance from an economic standpoint and environment. The ability to create lasting roads leads to lower overall carbon emissions.

Current road transport authorities such as Transport for New South Wales (TfNSW) (Transport for NSW, 2021) and Austroads (Carteret, Comport, Metcalf, & Rebbechi, 2018) have design criteria for concrete pavements in terms of compressive strength, flexural, tensile, and slump, as presented in Table 1. However, one of the primary criteria often overlooked is abrasion resistance, which measures the wear and tear that is highly critical to pavement longevity. Also, there is no existing literature where investigations on GO incorporated concrete's performance are available to the authors' knowledge. Thus, this study aims to fill this research gap where GO incorporated concrete performance for abrasion is tested for high GO percentages ranging from 0.1% to 0.3%, higher than those values cited in the literature. The paper is laid out such that Section 2 describes the test setup and mix for the GO incorporated concrete, where both strength and abrasion are measured. Section 3 includes the results and discussions for the observed results in detail, and finally, Section 4 presents conclusions.

2 METHODOLOGY AND TEST METHODS

2.1 Constituent Materials

Cement, graphene oxide (GO), fine aggregates, coarse aggregates and water were used as basic materials in this research program. The polycarboxylate ether (PCE) based superplasticiser was considered the water-reducing admixture.

2.1.1 Graphene Oxide (GO)

GO material used in the present work (CGT-GO-001) was obtained from Ceylon Graphene Technologies Pvt Ltd, Sri Lanka. GO was obtained as a powdered sample and dispersed in an aqueous solution (Figure 1) with a concentration of 10 g/L. This mixing process facilitates the easier and better incorporation of GO into the concrete mix.

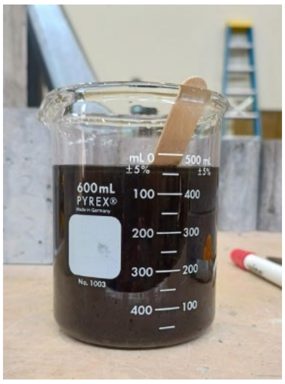

Figure 1: Graphene Oxide aqueous solution of 10g/L

The range of particle sizes in the solution used varied from 63-90 μm. Raman spectroscopy and FTIR results of the used GO material are shown in Figure 2 and Figure 3, respectively. Attenuated total reflection Fourier transform infrared (ATR-FTIR) spectra of the graphene oxide were recorded in the range of 800 to 4000 cm^{-1} at a resolution of 4 cm^{-1}. The sample was drop cast on the microscopic glass slides for the Raman spectroscopy tests. Four different spots were analysed. Parameters were set as follows, 532 nm; green laser was used with 20X optical zooming (Ceylon Graphene Technologies, 2021).

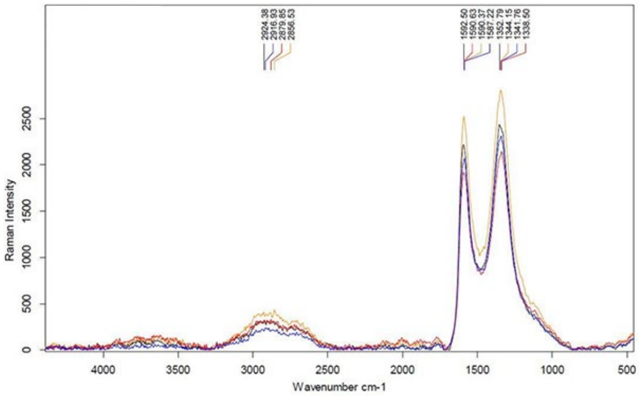

Figure 2: Raman spectroscopy results of the GO material used in the present work (Ceylon Graphene Technologies, 2021)

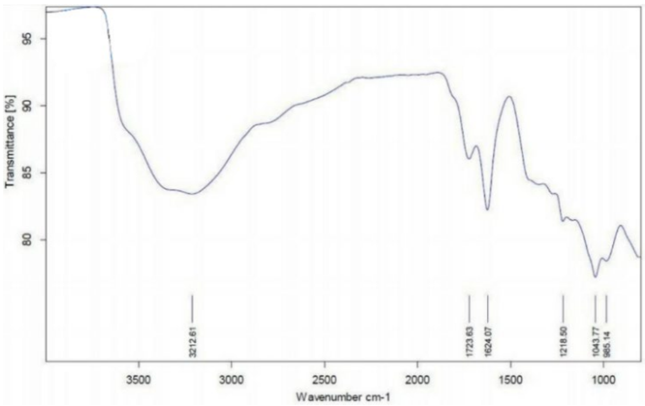

Figure 3: FTIR results of the GO material used in the present work (Ceylon Graphene Technologies, 2021)

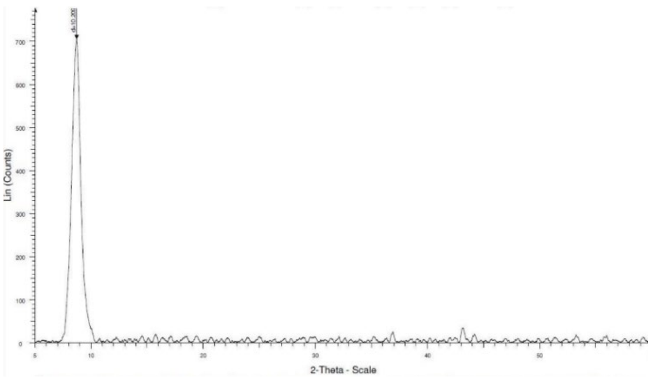

Figure 4: X-ray powder diffraction (XRD) results of the GO material used in the present work (Ceylon Graphene Technologies, 2021)

X-ray powder diffraction (XRD) results of the GO material used in the present work are shown in Figure 4. The sample was mounted on a sample holder. Parameters were set as follows, Cu Kα radiation (λ= 0.154 nm) over a 2θ range of 5−60° with a step size of 0.02° and a step time of 10 s (Ceylon Graphene Technologies, 2021).

2.2 Experimental Plan

In this experimental investigation, two sets of concrete mixes were prepared to evaluate the performance of GO incorporated concrete. For the first set of concrete mixes, higher percentages of GO (0%, 0.1%, 02% and 0.3%) were selected to conduct abrasion tests. The lower percentages of GO (0%, 0.03% and 0.08%) were selected in the concrete mix as the second set of concrete mixes to measure the compressive strength, workability and dry density of GO concrete.

2.3 Mix Design and Proportions

The mix proportions used in the present work are summarised in Table 1, where the contents of constituent materials for the nominal sample target compressive strength of 40MPa at 28 days. This strength requirement was explicitly chosen to abide by the requirements of TfNSW (Transport for NSW, 2021) and Austroads (Carteret et al., 2018), where the interested reader is directed to the references.

2.4 Test Methods

2.4.1 Abrasion Test

Abrasion tests were performed in accordance with the ASTM–C418-20 (ASTM International, 2020) standard to measure the relative resistance of concrete surfaces using a sand blasting apparatus. The abrasion tests were performed for GO incorporated concrete at the age of 7-days with mixes of 0% (CM-0), 0.1% (CM-4), 0.2% (CM-5) and 0.3% (CM-6). The GO percentages given before are based on the weight of cement. Block specimens having dimensions of 300mm × 150mm × 80mm were used, as displayed in Figure 5.

Silica granules of weight 600±25 g, retained through a 600-µm sieve but passed through an 850-µm sieve, were used as the blasting material. Specimens were blasted at a pressure of 410±1 kPa for 60 seconds. All specimens were submerged in water for 24 hours prior to testing. During the tests, the specimens were placed 75±2.5 mm away from the sand gun whereas per the standard. Each sample was sand blasted eight times where the craters were used to measure volume abraded.

At the end, the abrasion quantity was determined by the volume of abrasion using a clay fill (Figure 6) where results are presented as average volume of abrasion per sample which can be easily determined by the mass of clay required to fill the craters.

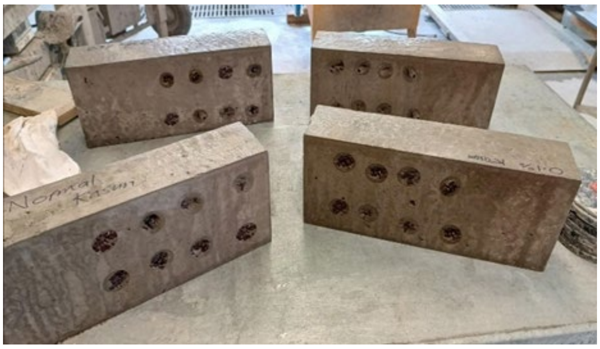

Figure 5: Specimens prepared for abrasion testing

Figure 6: Craters in abrasion test specimens filled with clay

Table 1: Mix Proportions for GO incorporated concrete

Constituent Materials	Control Mix	Compressive Strength, Workability and Dry Density			Abrasion Resistance		
	CM-0	CM-1	CM-2	CM-3	CM-4	CM-5	CM-6
GO %	*0.0*	*0.0*	*0.03*	*0.08*	*0.1*	*0.2*	*0.3*
Cement (kg)	*451*	*451*	*451*	*451*	*451*	*451*	*451*
GO (kg)	-	-	*0.135*	*0.361*	*0.451*	*0.902*	*1.353*
Fine aggregates (kg)	*573*	*573*	*573*	*573*	*573*	*573*	*573*
Coarse aggregates (kg)	*1163*	*1163*	*1163*	*1163*	*1163*	*1163*	*1163*
Water (kg)	*203*	*203*	*189*	*167*	*203*	*203*	*203*
Superplasticizer (kg)	-	*0.904*	*0.904*	*0.904*	-	-	-

2.4.2 Compressive Strength Test

Compressive strength tests were conducted as per AS 1012.9:2014 (Australian Standards, 2014) using cylindrical specimens having a diameter of 100mm and a height of 200mm. Six cylindrical specimens were prepared for each concrete mix to test the compressive strength in 7 days and 28 days. Samples were demoulded after a day of casting and then subjected to moisture-curing in the fog chamber until testing. The compressive strengths at 7 days and 28 days were obtained using a compression testing machine.

2.4.3 Workability and Dry Density

Concrete samples were prepared in accordance with AS 1012.3.1 (Australian Standards, 2014) for the conformity test for the slump. Properly dried mould rested on a smooth flat surface and filled with 3 layers of concrete after compacting them using compacting rod with 25 strokes per step. By maintaining a firm downward pressure, mould was removed in the vertical direction, waiting for concrete to retain.

The dry density of each concrete mix was calculated by measuring the dimensions and mass of three dry cylindrical samples at the age of 7-days and 28-days before conducting the compressive strength test.

3 RESULTS AND DISCUSSIONS

This section displays the results for abrasion, compressive strength, workability, and density of GO incorporated Concrete. For the Abrasion tests, higher GO percentages were used from 0.1% to 0.3%. The GO percentages used for the compressive strength test, workability, and density tests are from 0.03% to 0.08%, where tests were performed at 7 days and 28 days.

3.1 Abrasion Resistance

Table 2 tabulates the results for the abrasion test, where the mass of the clay is recorded and the average volume of abrasion obtained noting that the clay has a density of 1440kg/m^3. Figure 7 shows the volume abraded vs GO% graph. With respect to the nominal sample (CM-0), a reduction of 28%, 46% and 70% was obtained at GO% of 0.1% (CM-4), 0.2% (CM-5) and 0.3% (CM-6) respectively. As observed, the addition of GO can drastically improve the abrasion resistance of the concrete. More importantly, it must be noted that these tests were performed at 7 days as road pavements which are usually rehabilitated or newly paved, are usually opened to the public at a lower turnaround time.

Table 2: Test matrix results for abrasion

Sample	Start Mass (g)	End Mass (g)	Deficit (g)	No. of Craters	Average Volume Abraded (cm^3)
Nominal (0% GO)	*130.00*	*110.10*	*19.91*	*8*	*1.73*
0.1 % GO	*110.10*	*95.82*	*14.28*	*8*	*1.24*
0.2 % GO	*95.82*	*84.94*	*10.88*	*8*	*0.94*
0.3 % GO	*84.94*	*79.10*	*5.84*	*8*	*0.51*

The addition of nano-particles in the form of TiO_2 and SiO_2 has been reported to enhance the abrasion resistance of concrete (Li, Zhang, & Ou, 2006). It was also noted in (Li et al., 2006) that abrasion resistance and compressive strength have a proportional relationship, with increasing compressive strength, the abrasion resistance improves. However, as observed in the study, the compression test for GO percentages at 0.1%, 0.2% and 0.3% does not increase at the same rate of as the abrasion. This observation has not been reported in other literature pertaining to literature related to GO incorporated concrete. The causation of such mechanism can only be revealed by going through the microstructural investigations which needs to be further explored in future work.

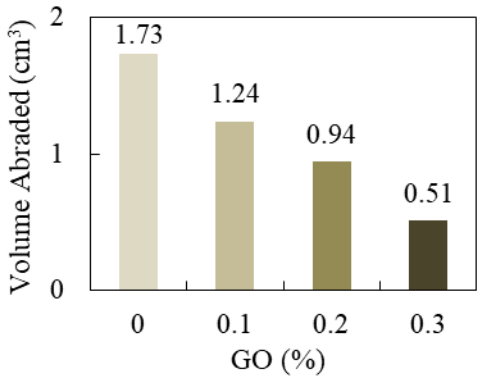

Figure 7: Abrasion test results

3.2 Compressive Strength

Compressive strength, workability and dry density results are given in Table 3 for all concrete mixes having different GO percentages.

The concrete mixes with different GO percentages (CM-2 and CM-3) have better compressive strength results than the control mix (CM-0). The 7-days and 28-days compressive strength results obtained for different GO percentages are shown in Figure 8.

Table 3: Test Results

Cement Type	Notation	Slump (mm)	Dry Density (kg/m3)		Compressive Strength (MPa)		Strength Improvement (%)	
			7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
0.00% GO	CM-0	75	2435	2427	32.75	44.93	-	-
0.00% GO + PCE	CM-1	195	2437	2433	35.71	48.78	9	9
0.03% GO + PCE	CM-2	135	2481	2484	38.57	51.21	18	14
0.08% GO + PCE	CM-3	95	2531	2493	45.45	56.40	39	26

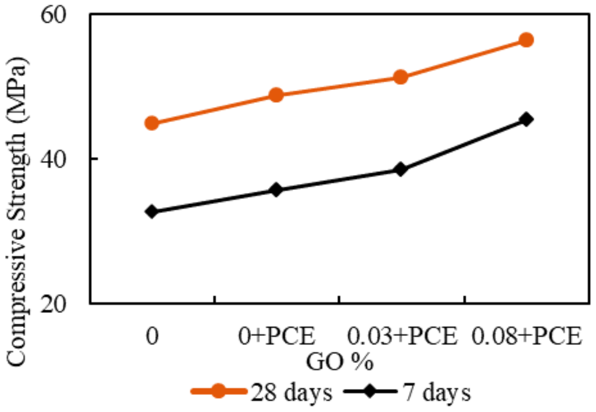

Figure 8: Compressive Strength Vs GO%

Compressive strength was drastically increased when increasing the GO percentage and the concrete mix with 0.08% GO, CM-4 has the highest strength value. When the GO percentage increased from 0.03% to 0.08%, the 7-days compressive strength increased from 38.57MPa to 45.45MPa, representing a strength improvement from 18% to 39% compared to the control mix. Same concrete specimens with 0.03% and 0.08% GO have shown a strength improvement of 14% and 26%, respectively, at 28-days compared to the control mix. These percentages of strength improvement indicate that the gain of compressive strength at the first 7-days was more predominant when compared to 28-days, as shown in Figure 9.

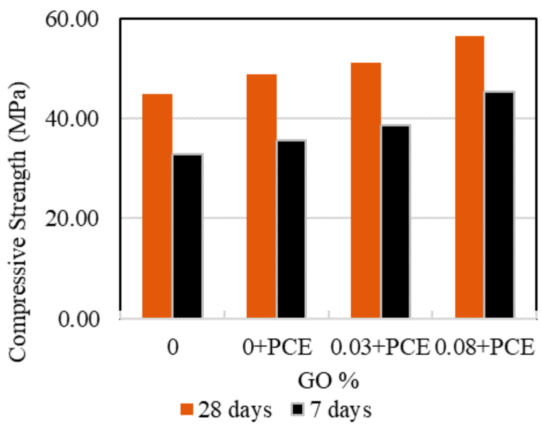

Figure 9: Strength comparison at 7-days and 28-days

These results conclude that GO particles were delivered a favourable platform in the concrete matrix by creating a nucleation site for hydration reaction at the early concrete stages.

The well-established bond between GO and the cement paste provides a favourable reinforcement in cement-based concrete composites. All concrete mixes having different GO percentages in this study have sufficient strength improvement at 28-days required for the application of rigid pavements. The high early-stage strength in GO incorporated concrete is a benefit for rigid pavements by opening the road for traffic usage.

3.3 *Workability and Dry Density*

The workability of GO incorporated concrete is an essential parameter for placing concrete. In the present study, the consistency of fresh concrete was obtained in terms of slump test value. The slump test results for different GO percentages with PCE (polycarboxylate ether) are shown in Table 3. The control mix without GO (CM-0) achieved a slump value of 75mm as designed. Then, for the same concrete mix, a superplasticiser dosage was added to obtain a slump value of 200mm, and the resulted value was 195mm (CM-1). The same superplasticiser dosage was used in the other two concrete mixes with 0.03%, and 0.08% GO content. These mixes were used to measure GO incorporated concrete's workability.

As shown in Figure 10, slump values were decreased gradually when increasing GO content in the concrete mix. When adding an aqueous form of GO by mixing it with water, the workability of the fresh concrete mix started to decrease gradually, and a stiffer and more cohesive mix was obtained as a result of it. There were 31% and 51% decrease in slump values as a percentage with the addition of 0.03% and 0.08% GO in the concrete matrix than the control mix without GO.

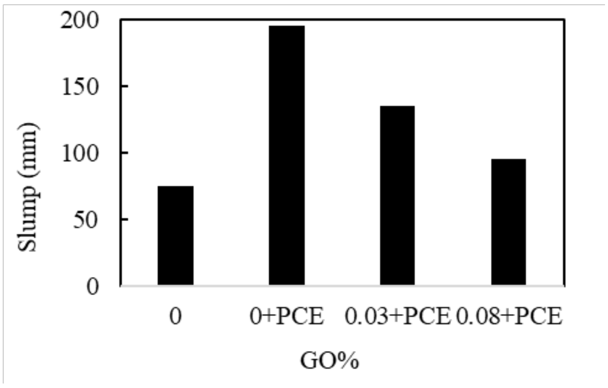

Figure 10: Slump of concrete vs GO%

The high specific surface area of GO absorbs a large amount of water from the fresh concrete mix to wet its surface. Therefore, the slump value of GO incorporated concrete mixes was linearly reduced when increasing GO content. PCE based superplasticiser can be introduced into the concrete mix to obtain the required workability.

Furthermore, the dry density of GO incorporated concrete is shown in Figure 11. The nominal sample and the nominal sample with the PCE superplasticiser are observed to have a similar density value of around 2440kg/m^{3,} which is very close to the density value quoted in the AS 3600:2018 (Standards Australia, 2018). As observed, the addition of PCE does not affect the density of concrete. With the addition of GO the density of concrete at 0.03% GO increased to 2480kg/m^3 and at 0.08% GO to 2540kg/m^3. These observations are in line with previous literature, where it is often found that there is a proportional increase in the concrete density (Heikal, Abd El Aleem, & Morsi, 2013). This is also observed here with the addition of GO to the concrete mix, where it is clear that at 0.03% and 0.08% of GO, the compressive strength and density of the concrete have increased.

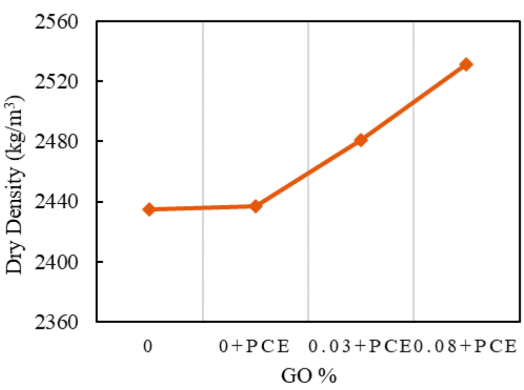

Figure 11: Density vs GO%

4 CONCLUSIONS

This manuscript presents experimental work conducted on Graphene Oxide (GO) incorporated concrete composite with the main emphasis on abrasion performance. Abrasion plays a critical role in the resistance of road pavement longevity due to the constant wear and tear that these surfaces are subjected to from moving traffic. To this end, the manuscript presents experimental tests for GO incorporated concrete, where strength, abrasion and workability are measured for different mix compositions. The primary outcomes of this research are listed below

1. The addition of GO to the cementitious mix improved the abrasion resistance, where at 0.3% of GO, the volume of abrasion had reduced by 70% compared to the nominal sample. Abrasion was measured at 7 days as it is expected that road pavements that are rehabilitated and newly paved roads would usually have to open before the concrete fully cures. Hence testing at seven days was more realistic for practical applications.
2. The strength of Concrete, in terms of compressive strength, also showed improvements of 39% and 26% at 7 days and 28 days, respectively, for GO incorporated concrete (GO – 0.08%) in comparison to the nominal sample.
3. As anticipated, the workability of the concrete mix was found to reduce due to the addition of GO. It was mentioned that adding polycarboxylate (PCE) superplasticisers was necessary to improve the slump. This is an essential addition as GO has a high surface area and absorbs water readily.
4. The density of concrete was found to increase with GO's addition, which correlates well with the compressive strength improvements.
5. It was shown that Compressive strength and Abrasion resistance are not proportional to one another, as usually mentioned for other nano-additives for concrete in previous literature.

In general, the addition of GO can significantly improve the properties of concrete in terms of its performance. Given that GO is hydrophilic and easier to extract from Graphite and hence cost effective in comparison to Pristine Graphene, GO can be considered for large practical scale industrial applications. Finally, the main advantage of incorporating GO is that it leads to the consumption of less cement to achieve similar strength to conventional concrete. This consequently leads to more sustainable construction and a low carbon footprint for structures built incorporating GO concrete leading to green infrastructure in future civil engineering applications.

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