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An Experimental Study on the Mechanical Performance of Concrete Enhanced with Graphene Nanoplatelets

Johana Jaramillo, Robin Kalfat, Dmitriy A. Dikin

***Abstract*—**The cement production process is one of the major sources of carbon dioxide (CO_2), a potent greenhouse gas. Indeed, as a result of its cement manufacturing process, concrete contributes approximately 8% of global greenhouse gas emissions. In addition to environmental concerns, concrete also has a low tensile and ductility strength, which can lead to cracks. Graphene Nanoplatelets (GNPs) have proven to be an eco-friendly solution for improving the mechanical and durability properties of concrete. The current research investigates the effects of preparing concrete enhanced with GNPs by using different wet dispersions techniques and mixing methods on its mechanical properties. Concrete specimens were prepared with 0.00 wt%, 0.10 wt%, 0.20 wt%, 0.30 wt% and wt% GNPs. Compressive and flexural strength of concrete at age 7 days were determined. The results showed that the maximum improvement in mechanical properties was observed when GNPs content was 0.20 wt%. The compressive and flexural strength were improved by up to 17.5% and 8.6%, respectively. When GNP dispersions were prepared by the combination of a drill and an ultrasonic probe, mechanical properties experienced maximum improvement.

***Keywords*—**Concrete, dispersion techniques, graphene nanoplatelets, mechanical properties, mixing methods.

I. Introduction

THE construction industry is one of the leading industries in the world, contributing considerably to the economic growth of many countries and providing a wide range of benefits. Nevertheless, the impact of this industry on the environment is significant [1], [2].

The use of concrete as a structural material is very common in the construction industry because of its high compressive strength, durability, and low cost. However, concrete is an extremely brittle building material and some of its major limitations include brittleness, low ductility, and low tensile strength. As an alternative environmentally friendly additive, GNPs have been proposed to enhance the engineering properties of concrete [3], [4]. Extensive research has demonstrated that GNPs increased the mechanical properties of paste cement, mortar, and concrete. For example, Wang et al. [5] reported the addition of 0.05 wt% improved the compressive and flexural strength of cement paste by 3% and 16.8% at 28 days, respectively. They also reported the addition of 0.05 wt% improved the compressive and flexural strength of cement paste by 7.5% and 23.7% at 7 days. Wang et al. [6] reported that the addition of 0.06 wt% GNPs resulted in increasing compressive and flexural strength by 11.1% and 17.8% at 7 days, respectively. Francesca et al. [3] found that the addition of 0.01 wt% increased the compressive and flexural strength of mortar specimens by 14% and 4% at 28 days, respectively. Additionally, the addition GNPs has been reported to improve the mechanical performance of concrete. For example, Chen et al. [7] prepared concrete specimens enhanced with 0.02 wt%, 0.05 wt%, 0.1 wt%, 0.2 wt%, and 0.3 wt% GNPs. They reported that compressive strength was increased by 18.61%, 22.40%, 19.78%, 8.84%, and 1.42%, respectively. Jiang et al. [8] reported that 0.025 wt% GNPs increased compressive strength at 28 days by up to 17%. Arslan et al. [9] prepared ultra-high strength concrete specimens with 0,035 wt%, 0.07 wt%, 0.14 wt%, 0.21 wt%, 0.35 wt%, 0.70 wt% GNPs. They reported that the maximum improvement in mechanical properties was obtained when 0.14 wt% GNPs was added. Indeed, the compressive and flexural strength increased by 24% and 96%, respectively.

On the other hand, the addition of GNPs has an adverse effect on fresh properties of concrete. It has been reported that the addition of GNP reduced workability of concrete. For example, Chen et al. [7] reported adding 0.4 wt% decreased workability of concrete specimens by up to 19%. Jing et al. [10] reported that cement paste specimens prepared with wt% and 0.4 wt% GNPs experienced 17.4% and 44% increase in workability, respectively. Two primary factors are responsible for the results. Firstly, GNPs have the ability to attract and absorb water onto their surfaces, thereby reducing the amount of water needed to achieve the desired workability. Secondly, due to their high van der Waals forces and large surfaces, GNPs tend to agglomerate.

In this research, concrete enhanced with GNPs is prepared and mechanical properties are assessed at 7 days. GNPs can be added to concrete via dry or wet dispersion techniques. In this research, GNPs are added to concrete via wet dispersion technique. The low stability of GNP dispersion results in producing concrete with many defects in the cement matrix. Those defects can compromise the mechanical performance of the concrete. To take full advantage of the benefits of GNPs on the mechanical properties of concrete, it is essential to produce a stable dispersion and to develop a proper mixing method. In this search, GNPs were dispersed in water by hand, with a drill

Johana Jaramillo and Robin Kalfat are with Swinburne University, Melbourne, VIC Australia (e-mail: jjaramillorestrepo@swin.edu.au, rkalfat@swin.edu.au)

Dmitriy A. Dikin is with Temple University, Philadelphia, Pennsylvania, USA (e-mail: ddikin@temple.edu)

or using an ultrasonic probe. Consideration was given to the different parameters that can affect the stability of GNP dispersions, including dispersion time, GNP concentration, and sonication duration. For the mixing methods, the following parameters were taken into consideration: type of mixer, and mixing time.

II. Materials

As a cementitious material, ordinary Portland Cement (OPC) is used to prepare concrete specimens. The OPC cement is fully compliant with Australia Standard AS3972 for Type GP cement. As coarse aggregates, crushed granite with diameters of 7 mm, 12.5 mm and 20 mm was used. As fine aggregates, washed sand with a diameter of 0.84-2 mm was used. An aqueous graphene paste consists of 32% pure graphene particles and 68% water was used. The materials used in this study are presented in Fig. 1. The physical properties of coarse and fine aggregates are presented in Tables I and II.

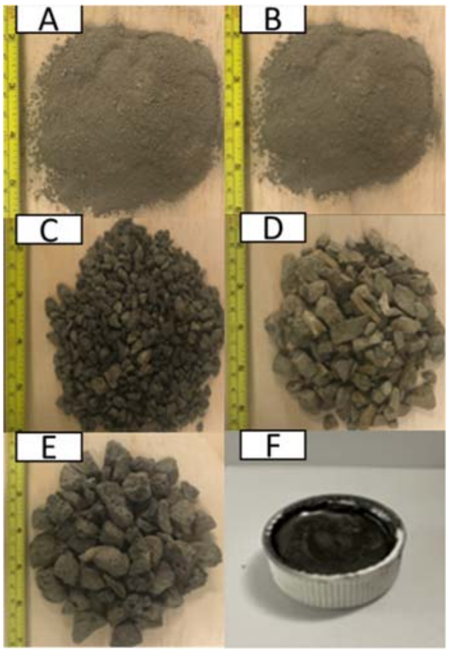

Fig. 1 Materials used in the study: A) cement, B) sand, C) 7 mm, D) 14 mm, and E) 20 mm

TABLE I
PHYSICAL PROPERTIES OF COARSE AGGREGATES

Aggregate size	20 mm	14 mm	7 mm	Standard
Apparent specific gravity (oven-dry)	2.74	2.68	2.32	ASTM C127
Density	2.58	2.57	2.23	ASTM C127
Specific gravity (SSD)	2.64	2.61	2.27	ASTM C127
Absorption %	2.22	1.59	1.88	ASTM C127

TABLE II
PHYSICAL PROPERTIES OF FINE AGGREGATE

Aggregate size	Sand	Standard
Apparent specific gravity (oven-dry)	2.25	ASTM C127
Density	2.01	ASTM C127
Specific gravity (SSD)	2.11	ASTM C127
Absorption %	5.34	ASTM C127

III. Mixing Procedure and Specimens' Preparation

A. Preparation of GNP Dispersion

GNPs were dispersed in water using different wet techniques. In the first group of GNP dispersion experiments, GNPs were dispersed in water using an ultrasonic probe for 5 mins. The study used an ultrasonic probe with a power output of 500 W and a probe frequency of 20 kHz. Sonication was done every 2.5 minutes to prevent overheating of the GNP dispersion. In the second group of GNP dispersion experiments, GNPs were dispersed by using an ultrasonic probe for 20 mins. In the third group of GNP dispersion experiments, GNPs were dispersed in water by combining a drill and an ultrasonic probe. In this group, GNP dispersions have various GNP content. The equipment used for the preparation of GNP dispersion is presented in Fig. 2.

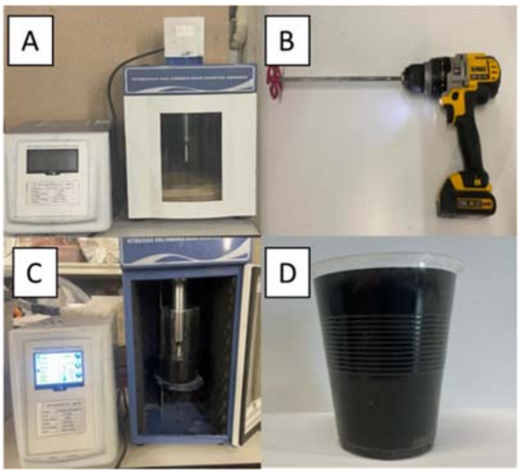

Fig. 2 Equipment used for preparing GNP dispersions: A) Sonicator, B) Drill, C) Sonicator and GNP dispersion, D) GNP dispersion

B. Introduction of GNP Dispersions to Concrete

In mixing method 1: concrete ingredients were mixed for 5 minutes in a rotating mixer. Then, 80% of the water was added and mixed for 5 minutes. Group 1 GNP dispersions were added to the mixture and mixed for 5 minutes. In mixing method 2: concrete ingredients were mixed for 5 minutes in a rotating mixer. Group 2 GNP dispersions were added to the mixture and mixed for 5, 10, 15, 25, 30 minutes. In mixing method 3: concrete ingredients were mixed for 5 minutes in a rotating mixer. Group 3 GNP dispersions were added to the mixture and mixed for 30 minutes. The materials are mixed in an agitator which is presented in Fig. 3. A summary of the dispersion techniques and mixing methods is presented in Table III.

C. Concrete Specimens' Proportions and Dimensions

As per AS 1012.8.1:2014, specimens are prepared and cured. Concrete specimens have a 100 mm diameter and a 200 mm height. Prismatic concrete specimens have a cross-sectional area of 75 mm by 75 mm, and a length of 290 mm. Mixture proportions for concrete specimens are: cement 1, washed sand 2, coarse aggregate 5.05, and water 0.60. Concrete specimens for compressive and flexural strength tests are presented in Fig. 4.

Fig. 3 The equipment used for mixing all materials (agitator)

TABLE III
DISPERSION TECHNIQUES AND MIXING METHODS

Test	Graphene (%)	Dispersion technique	Dispersion time	Mixing time
f_c	0.00%	Control	0	5+5
	0.25%	hand	5	5+5
	0.25%	sonication	5	5+5
	0.00%	Control	-	5+30
	0.25%	sonication	20	5+15
	0.25%	sonication	20	5+30
f_c and f_r	0.00%	Control	-	5+30
	0.10%	Drill + sonication	5 + 20	5+30
	0.20%	Drill + sonication	5 + 20	5+30
	0.30%	Drill + sonication	5 + 20	5+30

f_c= Compressive strength, f_r= Flexural strength

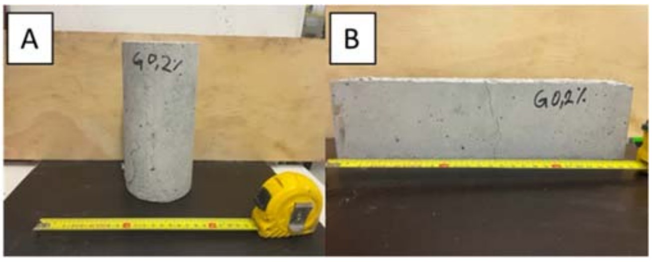

Fig. 4 Concrete specimens: A) Cylindrical specimens for compressive strength test, B) Prismatic specimens for flexural strength test

IV. TESTING

A. Compressive Test

The compressive strength is determined in accordance with AS 1012.8:2014. Compressive strength was determined after 7 days of curing. Tests are performed with a Tecnotest 2000 kN compression machine at 0.5 N/mm^2/s (MPa/s).

Fig. 5 Tecnotest 2000 kN compression machine

B. Flexural Test

The flexural strength is determined in accordance with AS 1012.11-2000. Tests are performed with MTS 50 KN machine at a loading pace of 0.5 N/mm^2/s (MPa/s).

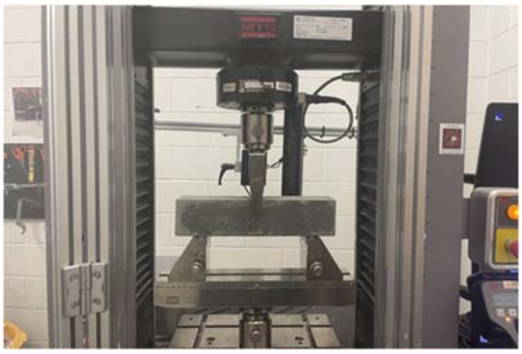

Fig. 6 MTS50 KN machine

V. RESULTS AND CONCLUSIONS

A. Effect of Sonication

The variation in compressive strength can be seen in Fig. 7. The addition of GNPs to concrete specimens resulted in a slight increase in compressive strength. It can be seen that the compressive strength of concrete specimens was increased from 17.97 MPa to 20.32 MPa when GNP dispersion was ultrasonicated for 5 mins. This represents an improvement of 13.1% compared to control specimens. Hand-prepared GNP dispersion was much less effective when added to concrete. The compressive strength of concrete specimens was slightly increased from 17.97 MPa to 19.24, which is only a 7.1% improvement. From the results, it is clear that GNP dispersion prepared using sonication is the most effective mechanism for developing a dispersion that increases the mechanical properties of concrete. According to prior study the use of sonication can enhance the stability of GNP dispersion [11], thereby maximizing the benefits of adding GNPs to concrete. By contrast, Jiang et al. [8] reported that GNP dispersion prepared with sonication had an adverse effect on mechanical properties of concrete. They claim that sonication process reduced the size of the nanosheets which led to a reduction in mechanical properties.

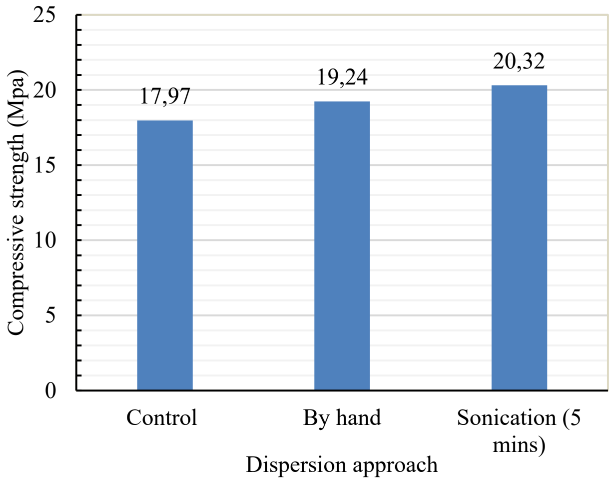

Fig. 7 The results of compressive strength obtained in mixing method 1

B. Effect of Increasing Mixing Time in Agitator

The variation in compressive strength can be seen in Fig. 8. The results demonstrated that increasing the mixing time of concrete ingredients and increasing sonication duration for preparing GNP dispersions resulted in higher improvement in the compressive strength. The maximum improvement in compressive strength was obtained when concrete ingredients and GNPs were mixed in the agitator for 30 minutes. Indeed, compressive strength was increased by up to 17.7% with respect to control specimens.

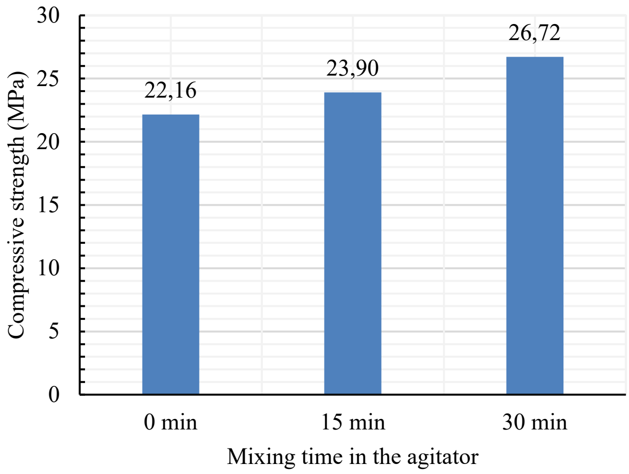

Fig. 8 The results of compressive strength obtained in mixing method 2

C. Effect of GNP Contents

The variation in compressive strength can be seen in Fig. 9. The addition of GNPs increased compressive strength. As a result, it is evident that the impact of GNPs depends on the amount of GNPs added. The result of this study is then compared with previous studies in which it was reported that the rate of improvement in compressive strength is directly related to the GNP content [7], [12]. In this study, compressive strength was enhanced by 12.8 %, 17.4 %, and 14.2% when mixes containing 0.1 wt%, 0.20 wt%, and 0.3 wt % GNPs.

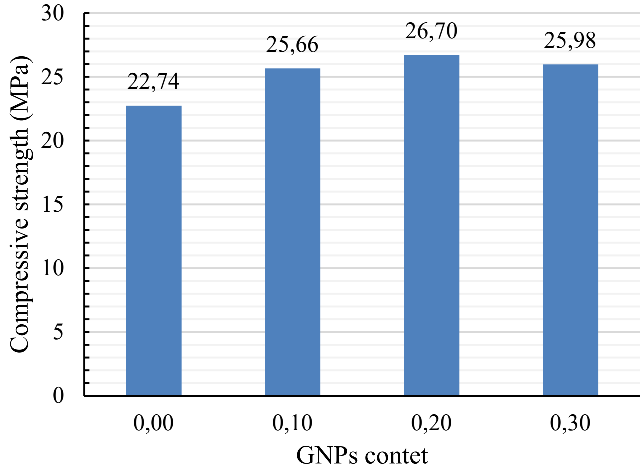

Fig. 9 The results of compressive strength obtained in mixing method 3

Fig. 10 represents the results of compressive strength obtained in this study compared with the results reported in the literature review. Chen et al. [7] prepared concrete specimens enhanced with 0.02 wt%, 0.05 wt%, 0.1 wt%, 0.2 wt%, and 0.3 wt%. They reported that the maximum improvement in compressive strength was obtained when 0.05 wt% was added. Indeed, compressive strength was increased by 22.40% with respect to control specimens. Arslan et al. [9] prepared ultra-high strength concrete specimens with 0,035 wt%, 0.07 wt%, 0.14 wt%, 0.21 wt%, 0.35 wt%, 0.70 wt% GNPs. They reported that the maximum improvement in compressive strength was obtained when 0.14 wt% GNPs was added. In fact, compressive strength increased by 24% with respect to control specimens. By comparing those studies with the funding of this study it can be determined that the compressive strength could be increased by adding a low content of GNPs. The optimum GNPs content is different in each study due to the fact that i) GNPs have different physical characteristic, ii) dispersion technique and mixing method are also different in each study. By contrast, Du et al. [13] reported that the addition of GNPs had a negligent effect on mechanical properties. It may be attributed to the fact that they added a high amount of GNPs, which can lead to agglomeration of nanoparticles, thereby adversely affecting the mechanical performance of specimens.

The variation in flexural strength can be seen in Fig. 11. The addition of GNPs enhanced flexural strength. The maximum improvement in flexural strength was observed when 0.2 wt% GNPs was added. Indeed, flexural strength increased from 3.32 MPa to 3.54 MPa which is an improvement of 8.6% with respect to control specimens. Once the GNPs content was higher than 0.2 wt%, the rate improvement was decreased. Flexural strength was slightly increased by 5.9%.

Fig. 12 represents the result of flexural strength obtained in this study is compared with the results reported in the literature review. In this study, flexural strength was enhanced by 0.7%, 8.6% and 5.9% when mixes containing 0.1 wt%, 0.20 wt%, and

0.3 wt % GNPs. By contrast, Arslan et al. [9] reported much higher results than those finding in this study. They reported that flexural strength of concrete specimens was dramatically increased by up to 95% when 0.14 wt% GNPs was added.

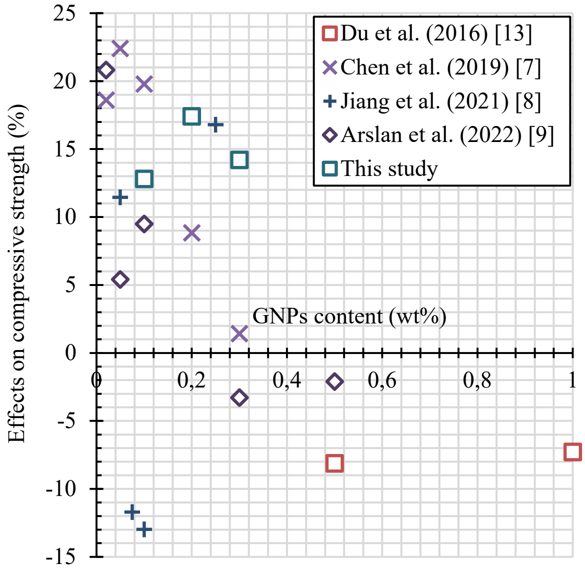

Fig. 10 Influence of GNPs on compressive strength of concrete

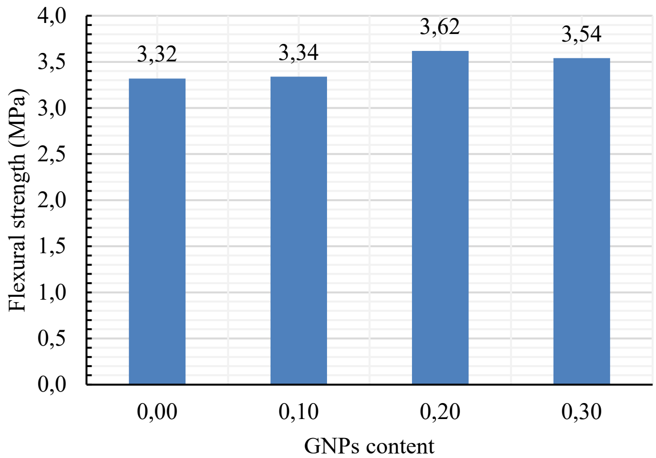

Fig. 11 The results of flexural strength obtained in mixing method 3

VI. Conclusion

The findings of this study are expected to have a direct impact on the construction industry since more environmentally friendly concrete will be produced. The mixing procedure is a key parameter that directly affects the mechanical properties of concrete. Therefore, in order to maximize the benefits of adding GNPs to concrete, the mixing procedure for concrete preparation should be carefully chosen. In this study, various approaches were used to prepare concrete with GNPs as an additive nanomaterial. In the mixing method 1, concrete specimens prepared GNP dispersion produced by using sonication experienced higher mechanical properties. Indeed, compressive strength was improved by 13.1% when GNP dispersion was ultrasonicated for 5 min. Another promising finding was observed in mixing method 2, by increasing both sonication duration and mixing time in the agitator the compressive strength is positively affected. Indeed, compressive strength was increased by up to 17.7%, when GNP dispersion was ultrasonicated for 20 minutes and all materials were mixed for 30 minutes. In mixing method 3, the present study confirmed the findings about the effects of adding different GNPs content. it was evident that the impact of GNPs on compressive and flexural strength was directly correlated with GNPs content. The maximum improvement of mechanical properties was obtained when 0.2 wt% GNP were added. In this case, GNP dispersion was mixed with dill, ultrasonicated for 20 minutes, and all materials were mixed for 30 minutes. Together, the present findings confirm that GNPs can be used a non-conventional nanomaterial in the construction industry. Overall, the results of this study are comparable to those of previous studies.

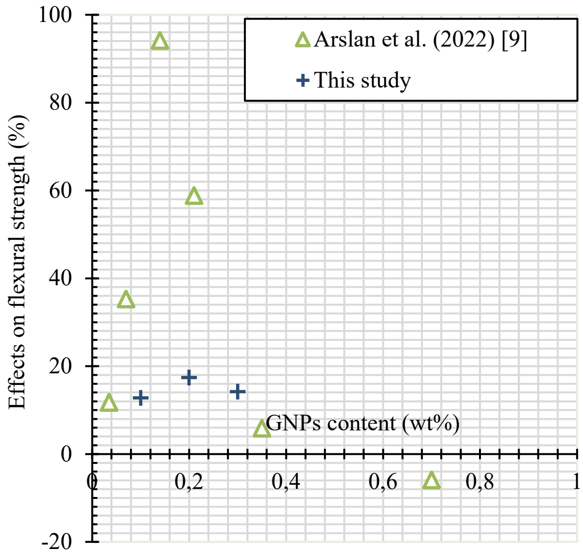

Fig. 12 Influence of GNPs on flexural strength of concrete

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References

[1] Salas, D.A., et al., *Environmental impacts, life cycle assessment and potential improvement measures for cement production: a literature review.* Journal of Cleaner Production, 2016. 113: p. 114-122.
[2] Mohamad, N., et al., *Environmental impact of cement production and Solutions: A review.* Materials Today: Proceedings, 2022. 48: p. 741-746.
[3] Lamastra, F., et al., *Toward a better understanding of multifunctional cement-based materials: The impact of graphite nanoplatelets (GNPs).* Ceramics International, 2021. 47.
[4] de Souza, F.B., et al., *Effective strategies to realize high-performance graphene-reinforced cement composites.* Construction and Building Materials, 2022. 324.
[5] Wang, B., R. Jiang, and Z. Wu, *Investigation of the mechanical properties and microstructure of graphene nanoplatelet-cement composite.* Nanomaterials, 2016. 6: p. 200.
[6] Wang, B. and B. Pang, *Mechanical property and toughening mechanism of water reducing agents modified graphene nanoplatelets reinforced cement composites.* Construction and Building Materials, 2019. 226: p. 699-711.

[7] Chen, G., et al., *Graphene Nanoplatelets Impact on Concrete in Improving Freeze-Thaw Resistance.* Applied Sciences, 2019. 9: p. 3582.
[8] Jiang, Z., O. Sevim, and O. Ozbulut, *Mechanical properties of graphene nanoplatelets-reinforced concrete prepared with different dispersion techniques.* Construction and Building Materials, 2021. 303: p. 124472.
[9] Arslan, S., N. Oksuzer, and H.S. Gokce, *Improvement of mechanical and transport properties of reactive powder concrete using graphene nanoplatelet and waste glass aggregate.* Construction and building Materials, 2022. 318.
[10] Jing, G., Z. Ye, and X. Lu, *Effect of graphene nanoplatelets on hydration behaviour of Portland cement by thermal analysis.* Advances in Cement Research, 2016. 29: p. 1-8.
[11] Sandhya, M., et al., *Ultrasonication an intensifying tool for preparation of stable nanofluids and study the time influence on distinct properties of graphene nanofluids - A systematic overview.* Ultrason Sonochem, 2021. 73: p. 105479.
[12] Alwash, D., et al., *Development of a new nano modified cement based adhesive for FRP strengthened RC members.* Construction and Building Materials, 2021. 277: p. 122318.
[13] Du, H.J., H.J. Gao, and S.D. Pang, *Improvement in concrete resistance against water and chloride ingress by adding graphene nanoplatelet.* Cement and Concrete Research, 2016. 83: p. 114-123.

Johana Jaramillo is a PhD candidate at the centre for sustainable infrastructure of Department of Civil engineering in Swinburne University of Technology. She received his BSc Engineering (Hons) in Civil Engineering from University of Antioquia, Colombia, in 2012. She has active research interests in sustainable construction materials, material science, and smart materials. Her recent research interest is primarily focused on nanomaterials for development of novel concrete.