Graphene Modified Cement

for High Performance Repair

by

Lim Yue Sheng

17003472

Dissertation submitted in partial fulfilment of

the requirements for the

Degree of Study (Hons)

Civil Engineering

JANUARY 2022

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATE OF APPROVAL

Graphene Modified Cement

for High Performance Repair

by

Lim Yue Sheng

17003472

A project dissertation submitted to the

Civil Engineering Programme

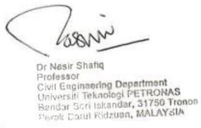
Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(CIVIL ENGINEERING)

Approved by,



____

Prof. Dr Nasir Shafiq

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

January 2022

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the reference and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

LIM YUE SHENG

ABSTRACT

Cracking occurs in concrete when it is subjected to loading that is beyond its strength capacity. Repair of the concrete can be performed by filling the cracks with cement mortar as a repair material. With the advent of graphene, which possesses remarkable properties, an ultra-high-performance repair material for concrete can potentially be developed by incorporating graphene nanoplatelets (GNP) into cement mortar. Notwithstanding the superior mechanical properties of GNP, determination of its optimum content as a constituent of the cement mortar is essential to maximize the performance of the repair material. Therefore, the effect of incorporating different percentages of GNP on the performance of cement mortar, as a repair material for concrete, was investigated. Cylinder specimens of concrete were subjected to compressive loading until cracking occurs. Specimens of cement mortar that contain GNP at 0%, 0.02%, 0.04%, 0.06%, 0.08% and 0.1% by weight of cement were employed to repair the concrete specimens. Pre- and post-crack compressive strengths of the concrete specimens were measured. Flexural strengths of dog bone-shaped specimens of the cement mortar were also measured to validate the compressive strength data. Based on the findings, 0.02 wt% GNP cement mortar possessed the highest capability in retaining the compressive strength of post-crack concrete specimens to the compressive strength of pre-crack concrete specimens by 70%. While 0.02 wt% GNP cement mortar had the highest tensile strength and the results showed that there was a positive correlation between the tensile strength of the cement mortar and the percentage of GNP by weight of cement. Lastly, 0.02 wt% GNP cement mortar was able to surpass the plain cement mortar in terms of strength capacities and thus its potential should be explored deeper.

ACKNOWLEDGEMENT

First of all, the author would like to express special gratitude to Professor Dr. Nasir Shafiq for allowing me to work on this project. Besides that, the guidance and thoughtful advice from Prof. Dr. Nasir Shafiq helped lead the author throughout the journey. Not only that, the author would like to thank both of the graduate assistants who are Mr. Fouad Ismail and Mr. Narindas for their technical guidance throughout the laboratory works.

Secondly, the author would like to take this opportunity to acknowledge the technologists of Concrete and Heavy Structure Laboratory of Universiti Teknologi Petronas for their assistance in carrying out the laboratory works as well as the Department of Civil and Environmental Engineering of Universiti Teknologi Petronas for creating this meaning project research.

Lastly, the author would like to thank both of the parents for their extensive encouragement and continuous support from the beginning until the end of this journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF STUDY

Although concrete is commonly used on building sites, its limitations, such as low tensile stress, can cause flexural cracks. However, present design approaches for controlling cracking with traditional steel reinforcement are insufficient to prevent fracture widths from widening over time due to other factors such as shrinkage. Although most destructive processes cannot be prevented, they can be slowed down with further treatment. This means that while there is no way for concrete to prevent flexural cracks, the research and development of superior flexural fracture repair materials should continue. Nanotechnology for concrete is advancing at a rapid pace these days. It is common to make the nano cement composite the main constituent for structural applications, especially during concrete placement in the construction industry but not as the concrete repair material. Moreover, the study on applying nano cement composite for sealing tiny cracks on the concrete surface is still less and countable. The anticipated hypothesis of this study is the existence of a strong bond between the surface of existing concrete and the nano cement composite such as GNP cement mortar. The strong bond is one of the criteria which is important in the control of crackings.

For this study, there is a limitation in which the size of crack within the ordinary concretes could not be controlled. The way to cope with this limitation is through the mixing of 35 MPa cylindrical concrete specimens. In relative to this, the concrete specimens could resist the high magnitude of crack loading without having a serious collapse or fracture. The crack pattern was anticipated to be formed in longitudinal on all of the samples and this may make the repairing works easier.

1.2 PROBLEM STATEMENT

External load yields the bending, direct and tensile stresses. Followed by this, flexural crack is a main structural deterioration governed by those stresses. Particular attention is required to minimize these stresses and to produce materials that properly cope with these relative disadvantages. [1] At the same time, the early age of concrete is extremely low in tensile strength as it is increasingly developed with age (Safiuddin et al., 2018). This means that the concrete cracking would be happened in the short period after being placed. The tensile stress could cause the flexural crack on the surface of concrete if it is surpassing the tensile strength of early age concrete. This crack would develop and propagate into the full depth of concrete if left aside. Excessive cracking resulting from external loads is one of the most common factors of uncontrollable damage in concrete structures. Not only that, the evaporation of water from the surface of concrete might induce tensile stress if it is faster than the bleeding rate. The stress could lead to cracks and it is common within a few hours of concrete placement. Therefore, repairing activity should be carried out to bring back the functionalities of concrete.

1.3 OBJECTIVE

The principal aim of this study was to develop a high performance cement composite for repairing old or damaged concrete structures. To achieve the aim the following objectives were designed and tested:

1. To develop ordinary concrete of target compressive strength of 35 MPa as the base material and high performance graphene modified mortar for repairing the cracked concrete

2. To investigate the effects of various graphene content in the repair cement mortar to reinstate the strength of the cracked concrete specimens with respect to the initial strength of concrete.

1.4 SCOPE OF WORK

There were two main phases of this research; phase-1 was to develop and test the base materials using normal concrete of 35 MPa. The second phase includes the repair of cracked cylinders tested in phase-1 and repaired with the graphene modified cement mortar. After repair, the cylinders were let for settling and tested for reinstatement of the concrete strength. Finally, an analysis was done to determine the optimum graphene content for the reinstatement of the cracked sample strength.

In addition, this research consisted of three stages. The first stage was to execute and complete those phase-1 and phase 2 activities. It was the most time-consuming stage out of the three stages. Ordinary concrete mixing, concrete cylinders casting, curing, cracking of concrete cylinders through compression machine, mixing of GNP cement mortar and repairing or rectifying are the activities during the executing stage. The longest curing of concrete cylinders commonly takes 28 days. This implies that this work should be done as early as possible so that the consecutive activities could proceed. The coordination with the lab technologists was often during this stage. The purpose of this coordination was to book the time slot of using the testing equipment and ask for the materials.

Last but not least, the controlling and closing were the post-experiment stages. The interpretation of experimental results and completion of the dissertation were the main focused activities at the controlling stage. Before the closing of this project, there would be a viva presentation to the supervisor, internal examiner and external examiner. This viva presentation would be a platform for the author to explain the findings of this study.

CHAPTER 2: LITERATURE REVIEW

This chapter outlines the brief and critical review of various literature regarding the sub-topics as below:

2.1 THE NATURE BEHAVIOUR OF GNP

[4] Due to the strong Van der Waal force between the particles of GNP, they tend to agglomerate but not distribute into the cementitious matrix (Metaxa & Kourkoulis, 2018). Therefore, water is required during the mixing of cement mortar to weaken the Van der Waal forces between the particles and this acts as the dispersing agent. [5] The combination of mechanical treatment and surfactants is necessary to ensure that the GNP can be homogenously dispersed into cement composite (Papanikolaou et al., 2021). The homogenous GNP cement mortar makes itself good in concrete crack repairing due to the intimate bond with the existing concrete. The intimate bond is boosted by the surface energy of the GNPs which are mixed into the cement composite. The platelet shapes of GNP also enable them to block and divert microcracks of the cement composite, thus aiding in inhibiting the crack propagation across the depth and preventing the formation of the crack network within the existing damaged or cracked concrete.

2.2 MECHANICAL PROPERTIES OF GNP CEMENT MORTAR

The concrete crack is unavoidable and it is the challenge faced by every construction player. Since then, research on the application of graphene and its derivatives into the repair material become common. They are the ideal material due to their specific characteristic which is nano in size. One of the graphene derivatives is graphene nanoplatelets (GNP) and it is being studied for this project. [6] According to Metaxa & Kourkoulis (2018), GNP consists of multiple graphene layers with an extent thickness ranges from 3 to 100 nm. Due to this, it can be coupled with fine aggregate, water and cement to form the repair material for concrete crack. GNP cement mortar could act as a filler that fits onto the concrete crack and in turn, increase the compactness of concrete.

Simultaneously, the addition of GNP to the cement composite may improve the composite's mechanical qualities, such as compressive and tensile strength, making it the primary material for repairing concrete cracks. The inclusion of GNP alters the microstructure of the hydration crystal as well as the rate of hydration. The degree of compaction, followed by compressive strength, would be improved by altering the microstructure. [7] The inclusion of GNP would also result in a higher cumulative acoustic energy, which would promote the cement composite's improved tensile force resistance to cracking (Jiang et al., 2020). [8] The interlocking function of nanofiller-matrix and cement hydration promotion, in general, catalyse the development of mechanical properties, which may create further barriers against subsequent concrete cracking (Wang et al., 2020).

On the other hand, the wt% of GNP in the cement composite is a factor that governs the degree of mechanical properties. When the GNP cement mortar is used to seal the concrete crack, it could also enhance the fracture toughness. The fracture toughness is the resistance to further crack propagation or growth. [9] Hezaveh et al., (2021) stated that this increasing toughness is induced by the enhanced relative density corresponding to the addition of GNP. Not only that, the GNP cement mortar could fill the cracking width of concrete. This would yield a beneficial impact on the concrete by inhibiting the propagation of crack and then reinforcing the matrix. The crack resistance effect provided by GNP cement mortar is due to the introduction of GNP into cement paste.

An optimum amount of GNP incorporated in cement paste could stimulate the equal distribution of hydration products and eventually increase the compressive and tensile strength. [10] However, if the content of GNP is higher than its optimum content, the inverse impacts would be occurred such as declining compressive and tensile strength in cement composite and even becoming lesser than the controlled cement composites (Tao et al., 2019). Corresponding to the large content of GNP in a cement matrix, it would lead to a massive drop in mechanical properties, which consequentially limits the uses of GNP cement mortar as a repair material. Particular attention is needed to avoid this concrete crack by developing materials that properly address corresponding issues. This research has been carried out to provide insight on how and what is optimum wt% of GNP to influence the performance of the cement composite which would be used as repair material gradually.

The workability of cement composite determines how much GNP affects concrete strength. The low water-to-cement ratio causes poor concrete workability, which may limit graphene nanoparticle dispersion in the cement paste. While a high water-cement ratio helps to concrete's excellent workability, it may compromise its homogeneity. As a result, the microstructure of the concrete may not be effectively densified, preventing the concrete from achieving its remarkable mechanical qualities. As a result, one of the factors governing the mechanical properties of GNP cement mortar is the water-cement ratio. This demonstrates the need of keeping an eye on the water-cement ratio in order to get the best GNP cement mortar yield.

2.3 CONCRETE CRACK REPAIR

During this repair work, GNP cement mortar can be utilised to stiffen and strengthen the parts where the concrete structures that exposed to high mechanical stresses such as bending stress, direct stress and indirect stress. These zones are likely susceptible to cracking. All other parts of the concrete structure remain in ordinary structural concrete as these parts are subjected to relatively moderate exposure and less liable to cracking. The GNP cement mortar itself exhibits excellent mechanical properties in compressive and flexure strength. Therefore. this study tends to determine the compatibility associated with this material in the rehabilitation of concrete cracks.

The nature or attractive capability of GNP is to change the microstructure of cement composite which is regarded as the basic source of many mechanisms relative to the short-term and long-term performance of cementitious materials. One advantage of these nano-sized materials could be used as additives where they can densify the microstructure of cement paste and eventually enhance the mechanical properties of concrete. If the GNP are well dispersed within the cement composite, their fizzy edge structure would act as support for multidirectional loading and conventional microcrack fixation. When the conventional microcrack is extended to GNP, their fizzy edge structure could lengthen the way of propagation and more loading energy would be absorbed as well as used for the bearing and pulling effect of GNP. As a result, the mechanical properties of concrete compounds would be improved in corresponding to the optimization of microstructure within the cement composite.

[11] At the same time, nano-sized GNP could promote the wide-ranging distributed or dispersed network within the matrix (Meng & Khayat, 2016). This can in turn facilitate the densification of microstructure. The rapid strength gain of GNP cement mortar resulting from the densification of microstructure is a vital advantage for speedy rehabilitation. In typical, this material is capable of gaining higher compressive strength within a short time as compared to other repair materials. This material is capable of facilitating the inhabitation of concrete crack as it is rapid propagation if left uncured.

The correlation of compressive and tensile strength is directly proportional. This implies that the increase of compressive strength in concrete could drive the increase of tensile strength in concrete. The increase of compressive strength in concrete is deemed as the "bridging effect" of the GNP for microcracks and the "filler effect" for speeding up the hydration reactions of the cement composite. Due to GNP having both of these unique capabilities, it makes itself the candidate rather than PVA fibre for reinforcing the cement mortar. The GNP cement mortar would be eventually used as the repair material for concrete crack due to their nano size which could occupy the crack width.

2.4 MECHANISM OF COMPRESSIVE AND TENSILE STRENGTH ENHANCEMENT OF GNP CEMENT MORTAR

How does the addition of GNP to a cement composite improve the mechanical characteristics of the concrete? In general, the change of cement hydration reaction can be used to explain the strengthening of concrete by including GNP. To fully comprehend, it is crucial to recollect some basic notions about this reaction as well as relevant GNP features. Fine and coarse aggregates are mechanically linked in concrete as a result of the hydration process between cement and water. The cement microcrystalline powder would undergo physical conversions to fibrous crystals containing calcium silicates, inoferrites, and calcium hydroxide (Ca(OH)2) after reacting with water molecules. [12] Not only that, but within the composition of cement, more than 40 different silicate crystals have been discovered, which create the calcium silicate hydrate (C–S–H) gel, which is one of the key ingredients responsible for the mechanical qualities of concrete (Chuah et al., 2014). Simultaneously, due to the introduction of GNP with high surface energy, C–S–H particles bind to them and serve as platforms for the creation of C–S–H gels. This procedure helps to improve the mechanical capability of cement composites. Indeed, GNP could result in a more durable C–S–H composite material than traditional concrete.

2.5 BOND STRENGTH BETWEEN REPAIR MATERIAL AND EXISTING CONCRETE

[13] Nanoparticles of GNP can speed up cement hydration due to their high activity compacting microstructure and in turn increase the bond strength within the cement composites (Pershin et al., 2020). The bonding strength between GNP, cement and sand is responsible for toughening nano-cement composite. The GNP, sand and hydration products of cement can connect as an organic whole which implies that the bond strength between the GNP and the other elements is strong enough. However, the high-performance repair material must not only possesses a strong bond within its matrix but possesses a strong bond strength with the existing concrete. [14] The bond between the original concrete and new repair material is critical, and it must enable a continuous transfer of the design loads as well as preferably approach the original concrete's initial strength (James et al., 2020). This characteristic is required to assess to determine the compatibility of GNP cement mortar as the concrete repair material. The strong bond strength could bring the durability of existing concrete and make it able to last longer. Not only that, the strong bond could resist the subsequent stresses which might be able to cause debonding of existing concrete and repair material.

Information on the compatibility of individual repair materials with existing concrete is scarce. The majority of the information available is focused on the characteristics of individual repair materials rather than composite materials made up of repair materials and existing concrete. The goal of this research is to investigate how compatible repair materials are with existing concrete based on compressive strength. Slant shear and direct shear tests are commonly used to assess the bond strength between the repair material and the existing concrete. Rather than that, the compressive strength of the pre-damaged concrete and the compressive strength of the post-damaged concrete mended with the repair material are compared in this study. As long as the findings reveal that the compressive strength has increased, the bond strength between the existing concrete and the repair material is strong. While the data demonstrate a decrease in compressive strength, they also reveal a weak link between the old concrete and the repair material. Table 2.1 contains the critical review of various literature to find the gap in the existing research.

TABLE 2.1: Summary of critical review from various literature

Author	Findings	Variables
Metaxa & Kourkoulis (2018)	The strong Van der Waal force between the particles of GNP, they tend to agglomerate but not distribute into the cementitious matrix.	Therefore, the water is required during the mixing of cement mortar to weaken the Van der Waal force between the particles and this act as the dispersing agent.
Papanikolaou et al., (2021)	The combination of mechanical treatment and surfactants is necessary	This is to ensure that the GNP can be homogenously dispersed into cement composite
Metaxa & Kourkoulis (2018)	GNP consist of multiple graphene layers with an extent thickness ranges from 3 to 100 nm.	Due to this, it is able to be coupled with fine aggregate, water and cement to form the repair material for concrete crack. GNP cement mortar could act as filler that fits onto the concrete crack and in turn, increase the compactness of concrete.
Jiang et al., (2020)	The addition of GNP would also yield a higher	This acoustic energy stimulates the increased tensile force resistance of

	cumulative acoustic energy.	the cement composite to the cracking.
Hezaveh et al., (2021)	The fracture toughness is the resistance to further crack propagation or growth.	The increasingly fracture toughness is induced by the enhanced relative density corresponding to the addition of GNP.
Tao et al., (2019)	The content of GNP is higher than its optimum content, the inverse impacts would be occurred ,	One of the impacts is loss of compressive and tensile strength in cement composite and even become lesser than the controlled cement composites,
Meng & Khayat (2016)	Nano-sized GNP could promote the wide-ranging distributed or dispersed network within the matrix.	This can in turn facilitate the densification of microstructure.
Liu, Li & Xu (2019)	GNP, sand and hydration products of cement are able to connect as an organic whole.	This implies that the bond strength between the GNP and the other elements is strong enough.
Pershin et al., (2020)	Nanoparticles of GNP can speed up cement hydration.	This is due to their high activity compacting microstructure and in turn increase the bond strength within the cement composites.
James et al., (2020)	The bond between the original concrete and new repair material is critical.	It must enable a continuous transfer of the design loads as well as preferably approaching the original concrete's initial strength.

2.6 Gap Analysis

The critical review of the literature indicated that repair or retrofit of old concrete material is continuously increasing due to gradual aging of structures and changing of operational conditions. However, there is least of the literature indicated the interaction between the repair material and the substrate (the old concrete). To design a correct repair material and analyze its compatibility with the substrate, nanomaterials and high performance composites are becoming a new agent for long lasting and high performance repair. The homogeneous load transfer and bond strength between the repair material and substrate are highly significant in retrofitting the old concrete material. If the load transfer is low and bond strength between repair material and substrate is weak, either one of them can lead to the failure of repair.

CHAPTER 3: RESEARCH METHODOLOGY

This project was through a laboratory experiment, which means that a large demand of materials was required to initiate the experiment. Before this, the setup of laboratory works was imperative for this project and should be properly planned. For example, a few items such as the material selection and size of concrete cylinder mould should be taken into consideration. Not only that, the volume for both mixing of ordinary concrete and GNP cement mortar should be calculated every single time. This is to avoid the unnecessary wastage of raw material which in turn could make this project costly. Figure 3.1 shows the methodology of this experimental work presented in the flowchart.

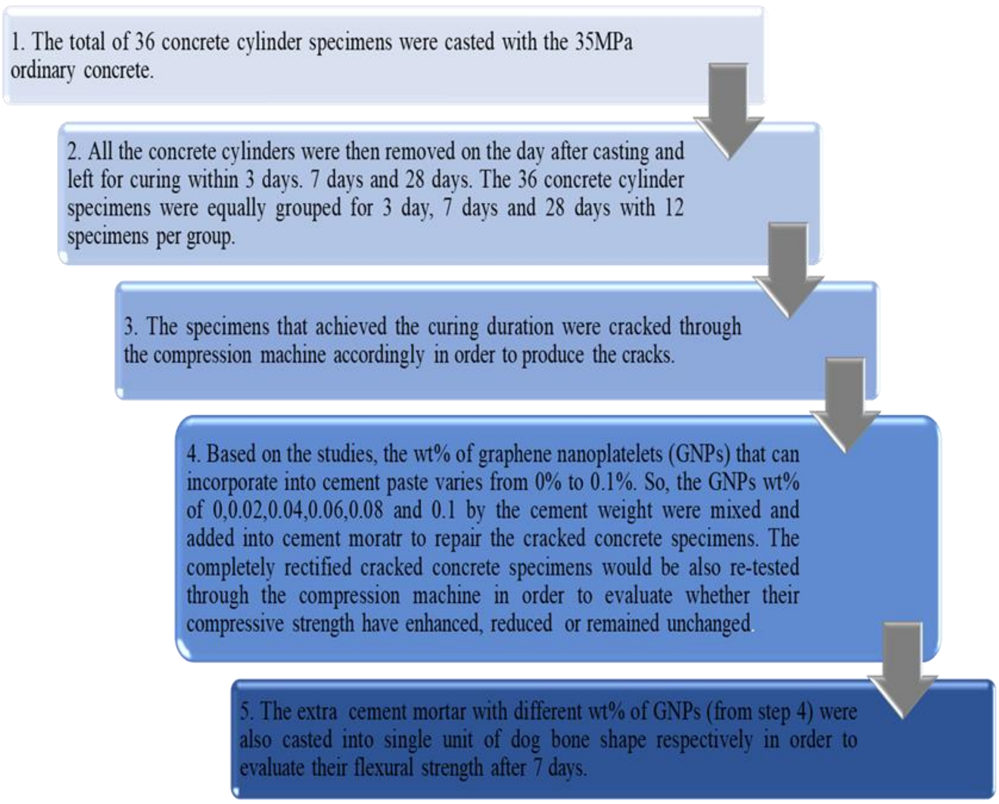


FIGURE 3.1: The Methodology Shown in Flowchart

Let discuss some procedures of this laboratory experiment. Firstly, the mixing of 35MPa of ordinary concrete followed by the concrete pouring would be performed.

This first step would be split into three days as there were 36 samples of the concrete cylinder to be made by this type of concrete. Secondly, all the 36 samples of the concrete cylinder would be cured and left for 3 days, 7 days and 28 days. Thirdly, after the curing of ordinary concrete cylinders, they would be cracked through the compression machine. The desired compression strength that is subjected to the ordinary concrete cylinders will be more than 35MPa to create the uniform concrete crack. The magnitude where the concrete specimens fail will be noted as initial compressive strength. Figure 3.2 shows the concrete mixing in the laboratory.

FIGURE 3.2: Mixing of 35 MPa Ordinary Concrete

Fourthly, it was time for the preparation and mixing of GNP cement mortar. This fourth step was divided into a few sub-steps which involved a lot of technique and skills. The first sub-step was the dispersing of GNP into the water and letting them fully dissolve into the water. Based on the study, the volume of GNP ranges from 0% to 0.1% of the total volume of cement. This range is workable and applicable in producing the excellent performance of GNP cement mortar. Therefore, the preparation and mixing of GNP cement mortar were repeated for 0 wt%, 0.02 wt%, 0.04 wt%, 0.06 wt%, 0.08wt% and 0.1 wt% of GNP to the total weight of cement. Each mix of GNP cement mortar would be used to repair 6 ordinary concrete cylinders that have cracks. Six of these ordinary concrete cylinders were equally divided into two per group which have been cured for 3 days, 7 days and 28 days respectively. At the same time, each mix of the GNP cement mortar would be cast into the dog bone shape of concrete mould.

FIGURE 3.3: Mixing of GNP Cement Mortar by Portable Cement Mixer with Rod

Fifthly, the post rectifying concrete cylinders would be then evaluated through the compression machine after strength gaining. This is to determine the enhancement or reduction of concrete cylinders in terms of compressive strength. While the dog boned shaped concrete would be evaluated to test their mechanical tensile strength after 7 days and make as the validation to the findings on the compressive strength. Figure 3.3 shows the compressive strength test for post-crack and repaired concrete specimens while figure 3.4 shows the tensile strength test for GNP cement mortar.

FIGURE 3.4: Testing of Compressive Strength for Post-Crack and Repaired Concrete Specimens

FIGURE 3.5: Testing of Dog Boned Shaped GNP Cement Mortar

The mix design of 35 MPa cylinder concrete is presented below. They would be as base material during the repairing work with the graphene modified cement mortar. Table 3.1 and table 3.2 show the parameters and their values used to design the 35 MPa cylinder concrete and steps for calculating the amount of materials for each specimen respectively.

TABLE 3.1: The Parameters Used For the Mix Design of 35 MPa Ordinary Concrete

Parameters	Values
Densiry of cement	1440kg/m^3
Density of 10mm coarse aggregate	1600kg/m^3
Density of fine aggregate	1766kg/m^3
Water/Cement	0.4

TABLE 3.2: The Quantitative Amount Used For Single Unit of 365 MPa Ordinary Concrete

	Amount
Dimension of concrete cylinder mould	0.15m (D) x 0.3cm (h)
Volume (m^3)	0.0053
Cement:Fine aggregate:Coarse aggregate	1:0.5:1
Cement (m^3)	0.0021
Fine aggregate (m^3)	0.0011
Coarse aggregate (m^3)	0.0021
Cement (kg)	0.0021 x 1440 = 3
Fine aggregate (kg)	0.0011 x 1766 = 1.9
Coarse aggregate (kg)	0.0021 x 1600 = 3.4
Water (kg)	0.41 x 3 = 1.2

While for the design mix of GNP cement mortar, it is dissimilar to the mix design of 35MPa ordinary concrete. The first difference is the incorporation of GNP. The difference largely depends on the wt% of GNP that incorporated onto the cement composite, The second difference is the absence of coarse aggregate in GNP cement mortar. It is obvious that the presence of coarse aggregate could influence the size of the repair material and make it could not embed into the crack that has tiny width.

The ratio of cement: water: sand is 1:0.5:1 in the mixing of cement mortar. The amount of materials for every batch of mixing depends on the numbers of concrete specimens that needed to be repaired and those mixes should be extra in order to cast it into the dog boned shape concrete mould. The procedures below show the calculation of a particular mix. The amount of cement, water and sand in every mix is kept the same but not the GNP. While table 3.2 shows the mixed design of cement mortar.

1) The 200 mm(d) and 300 mm(h) of PVC cylinder pipe would be used as the repairing mould.

Volume of PVC pipe = $\pi r^2 h$

$= (\pi)(0.1)^2(0.3)$

$= 0.00942\ m^3$

2) Net volume = Volume of PVC pipe – Volume of cylinder concrete

= 0.00942 – 0.0053

$= 0.00412\ m^3$

3) Let assume that a batch of 6 concrete cylinder specimens would be repaired in one shot by using the 0.02 wt% of GNP by weight of cement

Volume required = 6 x net volume x 10% extra for casting of single unit dog boned shape cement mortar

= 6 x 0.00412 x 1.1

$= 0.0269\ m^3$

4) In general, 500 kg of cement could be enough for 1 m^3 of concrete mixing. Therefore, 13.5 kg of cement could be used for 0.0269 m^3 of repairing as well as the casting of a single unit of dog boned shape cement mortar.

5) The amount of GNP to be used = 0.02% x 13.5 kg

= 0.0027 kg

= 2.7 g

While the ratio of 1:0.5:1 to cement: water: sand would be employed in the mixing of cement mortar.

TABLE 3.3: The Mix Design of GNP Cement Mortar

Material / % of GNP by weight of cement	Cement (kg)	Water (kg)	Sand (kg)	GNP (g)
0	13.5	6.75	13.5	0
0.02	13.5	6.75	13.5	2.7
0.04	13.5	6.75	13.5	5.4
0.06	13.5	6.75	13.5	8.1
0.08	13.5	6.75	13.5	10.8
0.1	13.5	6.75	13.5	13.5

CHAPTER 4: RESULT AND DISCUSSION

4.1 CHARACTERIZATION OF GNP

The source of GNP is XG Sciences, Inc. (Lansing, MI, USA). The type of GNP being used in this study was xGNP-C300. To determine its features, this GNP was subjected to tests such as Field Emission Scanning Electron Microscopy (FESEM) and X-ray diffraction (XRD). While the FESEM results shown in Figure 4.1

TABLE 4.1: Properties of GNP

Product	Density (g/cm^3)	Diameter (μm)	Thickness (nm)	Surface Area (m^2/g)	Carbon Content (%)	Elastic Modulus (GPa)	Tensile Strength (GPa)
xGNP-C300	0.2-0.4	≈2	≈2	300	99.52	1000	5

Based on the outcome of the XRD assessment, it shows that the characteristic peaks were at 26.5,42.3 and 54.6 with high intensity. While the FESEM clearly shows the particle size of GNP. The results of FESEM and XRD are shown in figure 4.1 and figure 4.2 respectively.

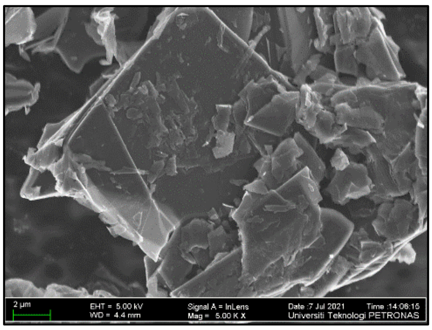


FIGURE 4.1: FESEM of GNP

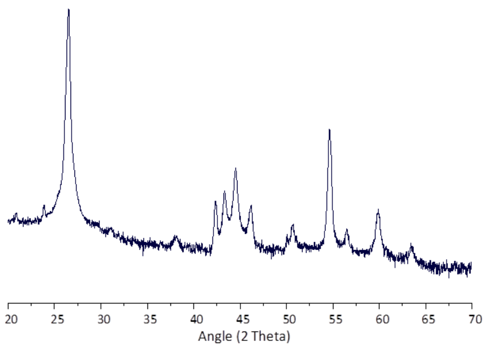


FIGURE 4.2: XRD of GNP

4.2 COMPRESSIVE STRENGTH FOR PRE-CRACK CONCRETES AND POST-CRACK CONCRETES REPAIRED WITH GNP CEMENT MORTAR

There were 36 ordinary concrete specimens cast for this experiment. Every 2 of them were cured for a specific number of days and then repaired by a certain mix of cement mortar. The results obtained from those 2 specimens would be averaged down. Despite the variation of initial compressive strength for ordinary concrete specimens, the final compressive strength for the composite compound consists of repair material and the ordinary concrete was more preferred for this study. The final compressive strength for the composite compound would be compared with the initial compressive strength for the composite compound and thus the difference between them was the desired output that the author seeks for. Figure 4.3, figure 4.4, figure 4.5, figure 4.6, figure 4.7 and figure 4.8 are graphs represent comparison in compressive strength before crack and after crack for that particular concrete specimens against their curing days.

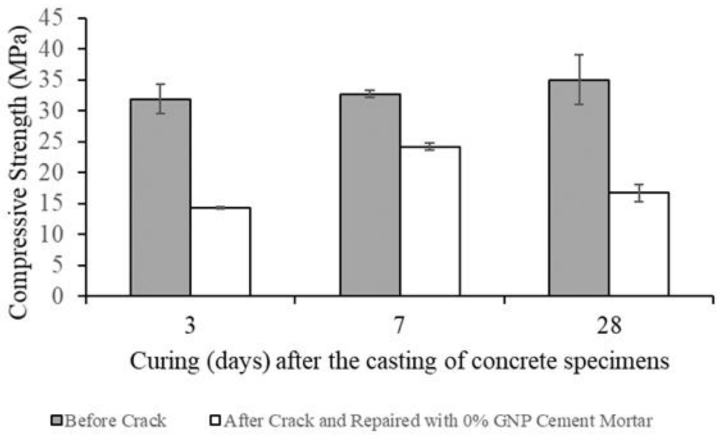


FIGURE 4.3: The Graph Compressive Strength (MPa) for those particular concrete specimens against Curing (days) after Casting of Concrete Specimens

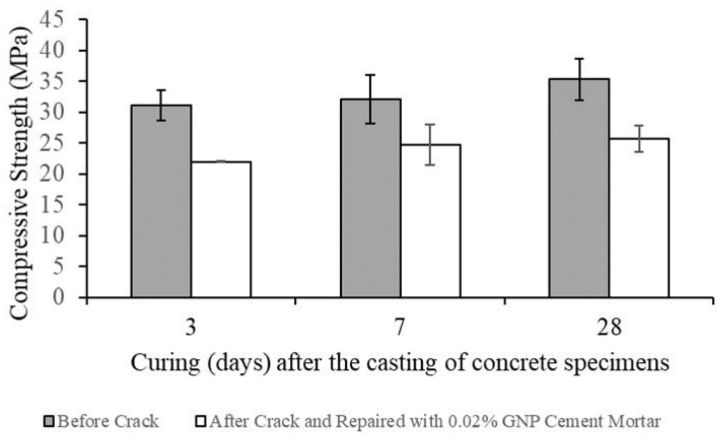


FIGURE 4.4: The Graph of Compressive Strength (MPa) against Curing (days) after Casting of Concrete Specimens

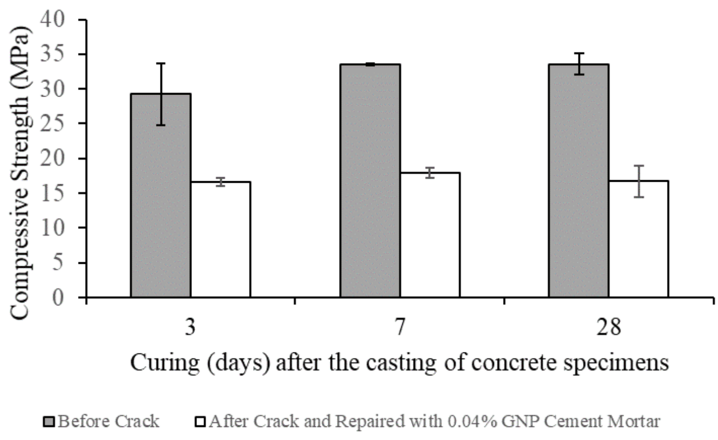


FIGURE 4.5: The Graph of Compressive Strength (MPa) against Curing (days) after Casting of Concrete Specimens

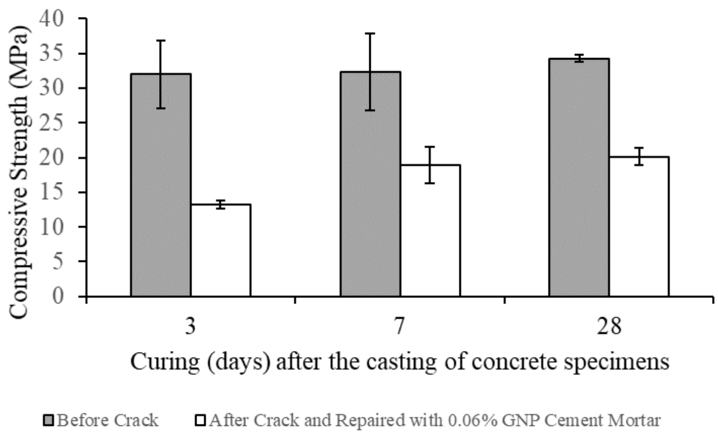


FIGURE 4.6: The Graph of Compressive Strength (MPa) against Curing (days) after Casting of Concrete Specimens

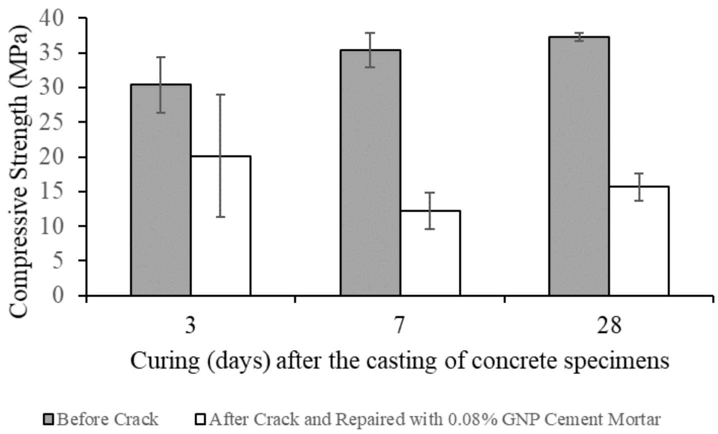


FIGURE 4.7: The Graph of Compressive Strength (MPa) against Curing (days) after Casting of Concrete Specimens

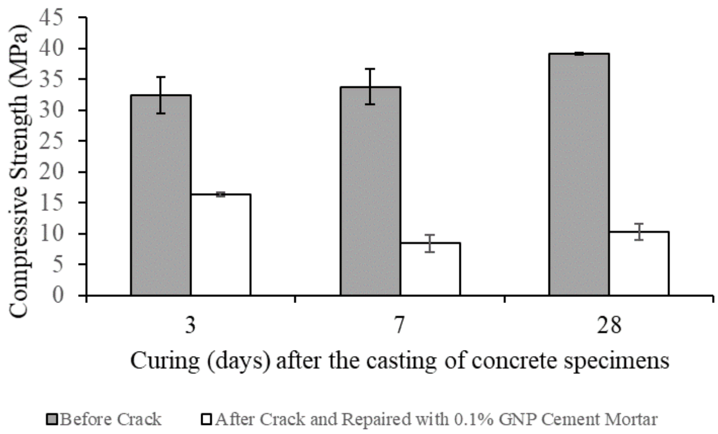


FIGURE 4.8: The Compressive Strength (MPa) against Curing (days) after Casting of Concrete Specimens

In overall, the compressive strength of post-crack concrete specimens after being repaired with GNP cement mortar was not retained as much as the initial compressive strength of pre-crack concrete specimens. But then there was the loss of compressive strength in the post-crack concrete specimens repaired with cement mortars if compared to the initial compressive strength of pre-crack concrete specimens. The cement mortars used consist of GNP that ranged from 0%, 0.02%, 0.04%, 0.06%, 0.08% and 0.1% by weight of cement. Those different percentages of GNP cement mortars were failed to keep the damaged concrete specimens to their original mechanical capacity in terms of compressive strength.

Apart from that, it was sure that these GNP cement mortars are far from becoming an ideal repair material. However, the 0.02 wt% GNP cement mortar could be the best and ultimate mix among other mixes of GNP cement mortar. Based on the analysis, this 0.02 wt% GNP cement mortar which is presented in figure 4.4 was able to retain around 70% of compressive strength for that particular concrete specimens after being repaired with it. The effectiveness of this cement mortar could be further proved as it was applicable for those particular concrete specimens which cured for 3 days, 7 days and 28 days. While the other cement mortar mixes could not retain the compressive strength of existing concrete as much as or higher than 70%.

At the same time, there was not the poorest mix of GNP cement mortar. Except for 0.02 wt% GNP cement mortar, the rest of these GNP cement mortars were able to retain the compressive strength of the post-crack concrete specimens with approximately 25% to 50% to their initial compressive strength. The cement mortars were not able to retain the initial compressive strength of the concrete specimens as much as the 0.02 wt% cement mortar did. However, it was undeniable that these GNP cement mortars were consistent in repairing the post-crack concrete specimens despite their curing time.

Apart from that, the findings showed that the relationship between bond strength of the GNP cement mortar and existing concrete and the content of GNP incorporated into cement mortar is inversely proportional. The higher content of GNP incorporated into cement mortar would not yield the higher bond strength of the GNP cement mortar and existing concrete. Therefore, the optimum content of GNP that could incorporate into the cement mortar was determined which was 0.02% by weight of cement. The 0.02 wt% GNP cement mortar was able to exhibit the ultimate mechanical capacity in terms of retaining the compressive strength of post crack concrete specimens.

Aside from that, there were some factors for this loss of compressive strength of post-crack concrete specimens after being repaired with the GNP cement mortars. The loss of this particular compressive strength could also be due to the weak bond strength between both components. The factors could be classified into technical and human factors. The first technical factor is due to these concrete specimens being left aside without being immersed into the water tank for the settling of cement mortar for the duration of 3 days. This duration could able to affect the quality of cement mortar and then initiate further crack due to plastic shrinkage caused by surrounding temperature. This was not surely true but the post repaired compressive strength of the concrete cylinders might be slightly affected by this plastic shrinkage.

Other than the plastic shrinkage, these 3 days of settling were not adequate for the gaining of compressive strength and even the settling was not catalyzed by the optimum temperature through the immersion into the water tank. Followed by this, the imbalance in the thermal expansion coefficient between the repair material and the existing concrete might occur. When two components of different coefficients of thermal expansion are bound together in relative to the constant temperature changes, stresses are generally be induced in between the interfaces. These stresses may cause failure at the interface or hinder the bonding between both components. Hence, the lesser compressive strength of post-crack and repaired concrete specimens as compared with the compressive stress of pre-crack concrete specimens was obvious.

In addition, the imbalance in mechanical compatibilities between repair materials and the existing concrete might significantly interrupt the quality of adhesion between both of the components. Commonly, the energy of adhesion between the existing concrete and repair material was lower than the cohesion energy of the existing concrete matrix itself. This was due to inequality in modulus material between the repair material and existing concrete. [15] The inequality in modulus might be due to the presence of coarse aggregate (Jacintho et al., 2020). There was a coarse aggregate in the ordinary concrete specimens but not in the GNP cement mortar. In this case, the post crack and repaired specimens might deform as more stresses had accumulated over the interface. At the same time, the high vulnerability of interfaces to damages due to stresses could ease the debonding process. This is because the interfaces might lose their resistivity to damages as the concrete specimens had been exposed to compressive loads during the production of cracks through compression machines.

Moreover, the high surface energy of GNP was used up during the mixing of cement mortar. [16] The consumption of this surface energy was to facilitate themselves to bind into the cement composite consisting of cement and water, especially during the hydration process. When this cement mortar was being used to repair the existing concrete surface, the surface energy of GNP had disappeared which made the low compatibility between the GNP cement mortar and existing concrete. Furthermore, steel reinforcement is useful and efficient in preserving concrete from the unstable crack formation. Steel reinforcement was not in use for this study. Although they were repaired with GNP cement mortar, the concrete specimens without steel reinforcement were weak in resisting the formation of cracks. According to the findings, ductile failure occurred as a result of increased loads, and the cracks propagated from the original fracture tips during compressive strength testing. It was determined that the initial compressive strength of the concrete specimens was higher than the post-crack and repaired concrete specimens as a result of this ductile failure. Figure 4.9 shows the propagation of crack from the original fracture tips.

FIGURE 4.9: The Propagation of Crack from the Original Fracture Tips

Furthermore, the final technical factor was the error in the cement mortar mixing sequence. [17] Stable GNP dispersions could be obtained in organic solvents or polar media like water. However, the dry dispersion of GNP was done by directly adding the GNP into the cement during the mixing of cement mortar. The first contact of GNP was the cement but not the water. The error in the mixing of cement mortar definitely would not make the distribution of GNP into cement composite easier. The effect due to the dry dispersion might cause the poorer dispersion of GNP within the matrix of cement composite and thus degrade the functionalities of GNP and finally the strength of cement mortar.

In terms of human factors, without the specific method in repairing the concrete cracks, a manual method was adopted to repair those cracked concrete specimens. For example, the concrete crack widths were sealed by rubbing the cement mortar through hand and trowel. It is undeniable that this way could only close up the crack width from the external surface but not from the internal body. Besides that, the presence of air bubbles embedded in between the existing concrete and repair material might cause the poor finishing of repair works. This manual way of concrete cracks repairing is one of the minor reasons why the lesser of compressive strength were in the post-crack and repaired concrete specimens.

Not only that, the other human factor is due to the surface of existing concrete was not cleaned before the placement of repair material. The loose material of the existing concrete might serve as the obstacle to the bonding between the repair material and existing concrete. Besides that, the mixing of GNP cement mortar was done through a portable cement mixer with the rod. Sometimes the mixing of GNP cement mortar by means of a mixer would cause unforeseen wastage such as spillage of the materials. The spillage would cause the ratio of materials to become uneven and different from the desired mix design. The uneven ratio of materials might cause the mechanical properties of cement mortar to become unattainable. The human factor is one of the reasons why the loss of compressive strength was in the post-crack and repaired concrete specimens.

Lastly, if all the human factors could be minimized and it would improve the accuracy of the results. Moving on, the findings on comparison between compressive strength of post-crack concrete specimens and pre-crack concrete specimens were within the expectation. The GNP cement mortar would be more aggressive than plain cement mortar in retaining the compressive strength of post-crack concrete specimens. However, none of the GNP cement mortar would be able to enhance the compressive strength of post-crack concrete specimens as compared with the initial compressive strength of pre-crack concrete specimens.

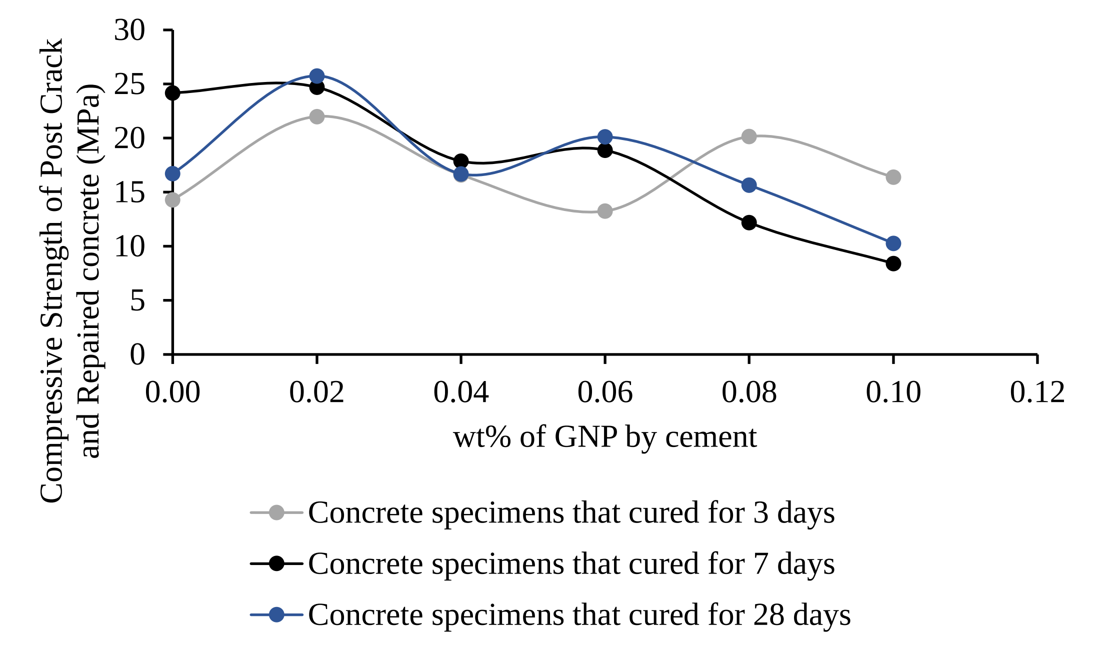


FIGURE 4.10: The Graph of Compressive Strength of Post Crack and Repaired Concrete (MPa) against wt% of GNP by Cement

Figure 4.10 shows the graph of compressive strength of post-crack and repaired concrete (MPa) against wt% of GNP by cement. On average, concrete specimens that were repaired with 0.02 wt% GNP cement mortar showed the lowest reduction in compressive strength as compared with concrete specimens that were repaired with other mixes of GNP cement mortar. The compressive strength of the post-crack and repaired concrete specimens were highest if 0.02 wt% GNP cement mortar was used. The 0.02 wt% GNP cement mortar was able to retain the compressive strength of all concrete specimens that were cured for 3 days, 7 days and 28 days. This was the advantageous characteristic exhibited by this particular mix of cement mortar as it showed consistency and effectiveness for all the concrete specimens despite their curing days. The 28 days was enough for the concrete to ultimately develop its mechanical strength. The results showed that the effectiveness of 0.02 wt% GNP cement mortar towards the post-crack concrete in which it has been cured for 28 days was a step forward to apply on the old and cracked concrete in the real construction industry.

4.3 TENSILE STRENGTH OF GNP CEMENT MORTARS-

The results obtained from previous evaluation found that a few numbers of phenomena arose from the interfacial interaction between the existing concrete and repair material. However, the study on the individual repair material without the presence of existing concrete should be performed. This is why the tensile strength test of this repair material was carried out through the Universal Tensile Machine (UTM). The findings of this test could use as complemental evidence in supporting or rejecting the compatibility of GNP cement mortar as the concrete repair material.

The cement mortars made up of a different percentage of GNP by weight of cement were cast into dog boned shapes. The aim of these dog boned shaped cement mortars were used to evaluate their tensile strength through Universal Tensile Machine (UTM). These dog boned shaped cement mortars were cured for 7 days in order to develop the maximum tensile strength. The findings of this evaluation would then be used to validate the findings on the compressive strength of existing concrete repaired with cement mortar. Figure 4.11 shows the graph of the tensile strength (kN) of cement mortar against the wt% of GNP by cement.

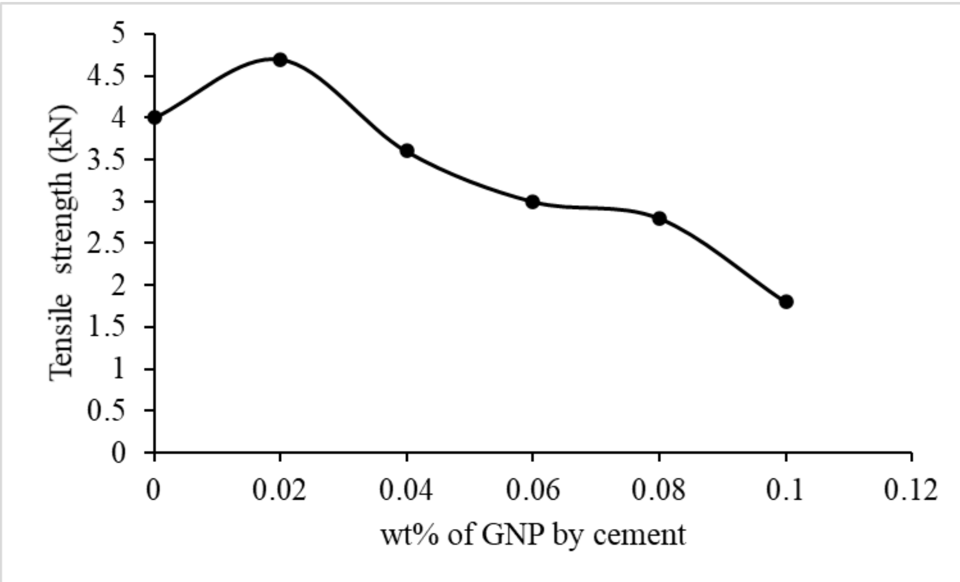


FIGURE 4.11: The Graph of Tensile Strength (kN) of Cement Mortar against the wt% of GNP by Cement

Based on the findings, 0.02 wt% GNP cement mortar possesses the highest tensile strength. The tensile strength was up to 4.7 kN and this was a shred of strong evidence in supporting 0.02 wt% GNP cement mortar was the best mix of the repair material. Together with this 0.02 wt% GNP cement mortar in which it possessed the best capability in retaining the compressive strength of existing concrete after being repaired with it. The retainable percentage was up to 71% and it was the highest among other designs mixed of cement mortars.

While the lowest tensile strength was attributed to 0.1 wt% GNP cement mortar. The tensile strength was down to 1.8 kN which was lower than 4.7 kN and 4 kN possessed by 0.02 wt% and 0 wt% cement mortar respectively. In comparison, the difference between the 0.1 wt% GNP cement mortar and the former was 62% while the difference between the 0.1 wt% GNP cement mortar and the latter was 55%.

In relative to the tensile strength test, it served as evidence that the GNP inclusion improves the tensile strength of cement mortar which is a requirement for rehabilitation of damaged concrete. The effectiveness of GNP inclusion could be seen through the comparison between the 0.02 wt% GNP cement mortar and the plain cement mortar. The 0.02 wt% GNP cement mortar exhibit higher tensile strength than plain cement mortar with 12.5%. The verification of 0.02 wt% GNP cement mortar through the compressive strength and tensile strength was able to make itself the optimum or ideal repair material for this study,

In addition, the highest tensile strength of cement mortar might be due to microstructure densification. [18] The porosity of cement composites could be considerably reduced, with densified microstructures, due to the combined action of such a nucleating and filling effect of graphene (Wu et al., 2021). The 0.02% GNP by weight of cement was sufficient and able to distribute uniformly within the matrix of cement composite. A sufficient amount of GNP might also bind with hydration products and thus develop the tensile strength firmly.

Last but not least, there was a significant positive relationship between the wt% of GNP by cement and tensile strength of cement mortar as the p-value obtained (= 0.007) is less than 0.05. The variable "wt% of GNP by cement" had a substantial influence on the tensile strength of cement mortar, showing that this feature is certainly a probabilistic variable, according to the analysis of variance (ANOVA). Furthermore, adopting the 0.02% GNP by weight of cement resulted in tensile strength that was 12.5% greater than those of cement mortar without GNP.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

There is a wide agreement among international researchers that concrete, the most used construction material has to be modified at the scale of nano, where nanotechnology is the future trend. This nanomodified construction material should be taken the processing and handling issue, safety, resources and cost into consideration. This consideration is crucial before the full potential of nanotechnology in concrete application could be realised.

Based on the experimental research, the findings discussed here clearly show that nanomodified cement composite through the introduction of graphene nanoplatelets (GNP) in cement mortar contributes to the extraordinary performance of strength and at the same time it is able to advance or expand the superior functionalities of cement composite. However, there is least in using this nanomodified cement mortar as concrete cracks repair material. Therefore, the author has been growing a deep interest to explore and find out this gap.

In addition, when the term "repair" is used, it refers to the process of returning an object to its original state. Not only that, the word "repair" indicates keeping an object in working order. The GNP cement mortar was not the best choice for restoring the fractured concrete sample to its original, usable state in this circumstance. [19] Successful concrete restoration means that there are no fractures in the concrete, even when it is subjected to loads (Czarnecki et al., 2020). However, the GNP cement mortar failed to rebuild the concrete and, more importantly, it failed to sustain the concrete's durability.

Despite the failure of this cement mortar in enhancing the mechanical properties of concrete such as compressive strength, however, this GNP cement mortar is expected to have the capability of satisfying multiple functions, especially acting as a barrier against concrete crackings by enhancing the interfacial interaction with the existing cracked concrete. This is because the plain cement mortar without the content of GNP possesses the least capability in retaining the compressive strength of post-crack and repaired concrete. Other than that, the capability of repair material in retaining the mechanical properties is an extremely desired characteristic for building up the durability of existing concrete structures in the long run.

The compatibility of repair material depends on its bond strength with the existing concrete. Dimensional compatibility is the potential of the material to withstand the load without further cracking or loss of bond. To ensure the realization of dimensional compatibility, the repair material should have good tensile ductility and lower or equal elastic modulus as compared to the existing concrete. Most important is that the repair material should be able to enhance the compressive strength of the existing concrete and have good interfacial interaction with existing concrete. It is undeniable that the 0.02% GNP cement mortar would be the potential and ideal repair material as compared to plain cement mortar. This 0.02% GNP cement mortar could attain the compressive strength of post-crack and repaired concrete specimens by 70% of its original compressive strength

[20] Another disadvantage of incorporating nanomaterial into the concrete is that when nanomaterial is used to improve strength, the particular concrete with better strength might have a higher density than the plain concrete, resulting in a heavier weight (Saleem et al., 2021). It is another challenge that should be taken into consideration because lightweight construction materials are now more preferred over heavyweight construction materials.

Last but not least, the repair material was allowed for settling and embedding into existing concrete within 3 days. This was due to the time constraint as mentioned above and the testing of compressive strength of the repaired concrete specimens was performed straight after settling. However, if settling time was extended to 28 days, the compressive strength of post-crack and repaired concrete specimens were expected to be higher. This was because the strength gaining of repair material and its interaction with existing concrete might take time.

5.2 RECOMMENDATION

First of all, the compatibility of the repair material with the existing concrete is critical in determining the repair's workability. The strong compatibility between those components allows the repair material to foresee the degree of changes over time and resist the pressures caused by volume changes caused by loads or environmental factors. However, because the repair material is unlikely to function in the same way as the existing concrete, therefore various studies can be carried out in finding out the repair material that can interact with the existing concrete as a whole is critical.

The objective is to determine the compatibility of GNP cement mortar as the repair material at the post-cracking stage. Except for this, the author would suggest that the GNP be incorporated into the cement composite as the extra reinforcement together with steel bars to the concrete. The author perceives that this incorporation would lead to the crack width control as well as inhibition of crack propagation and therefore the repair work to this crack could be minimized. However, this hypothesis is needed to be further investigated in the future.

Besides that, the concrete cracking could also be due to drying shrinkage. The characteristic of concrete that facilitates this shrinkage is the high permeability, This allows the water to be evaporated out from the surface of the concrete. The author perceives that the introduction of GNP into concrete could cope with this issue because it would lower the permeability of concrete and then limit the evaporation of water from the concrete surface. This issue is closely related to Malaysia due to the hot weather. However, this hypothesis is needed to be further analysed in the future.

Last but not least, lacking in recovering original concrete compressive strength with GNP cement mortar, further research and perspectives are needed for better results. . The potential of GNP should be fully realized and then utilized as the ideal repair compound. For example, the GNP cement mortar could be advanced to engineered cementitious composite (ECC) by adding the PVA fibre or fly ash as the mean of modifying the originality GNP cement mortar.

REFERENCE

[1] Safiuddin, M., Kaish, A. B. M. A., Woon, C.-O., & Raman, S. N. (2018). Early-Age Cracking in Concrete: Causes, Consequences, Remedial Measures, and Recommendations. *Applied Sciences*, *8*(10), 1730. https://www.mdpi.com/2076-3417/8/10/1730

[2] Baomin, W., & Shuang, D. (2019). Effect and mechanism of graphene nanoplatelets on hydration reaction, mechanical properties and microstructure of cement composites. *Construction and Building Materials*, *228*, 116720. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.116720

[3] Zhao, Y., Liu, Y., Shi, T., Gu, Y., Zheng, B., Zhang, K., Xu, J., Fu, Y., & Shi, S. (2020). Study of mechanical properties and early-stage deformation properties of graphene-modified cement-based materials. *Construction and Building Materials*, *257*, 119498. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.119498

[4,6] Metaxa, Z. S., & Kourkoulis, S. K. (2018). Dispersion of graphene nanoplatelets reinforcing type II cement paste. *Procedia Structural Integrity*, *13*, 2011-2016. https://doi.org/https://doi.org/10.1016/j.prostr.2018.12.215

[5] Papanikolaou, I., Ribeiro de Souza, L., Litina, C., & Al-Tabbaa, A. (2021). Investigation of the dispersion of multi-layer graphene nanoplatelets in cement composites using different superplasticiser treatments. *Construction and Building Materials,* 293, 123543. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.123543

[7] Jiang, Z., Sherif, M. M., Xing, G., & Ozbulut, O. E. (2020). Tensile characterization of graphene nanoplatelets (GNP) mortar using acoustic emissions. *Materials Today Communications*, *25*, 101433. https://doi.org/https://doi.org/10.1016/j.mtcomm.2020.101433

[8] Wang, J., Tao, J., Li, L., Zhou, C., & Zeng, Q. (2020). Thinner fillers, coarser pores? Acomparative study of the pore structure alterations of cement composites by graphene oxides and graphene nanoplatelets. *Composites Part A: Applied Science and Manufacturing,* 130, 105750. https://doi.org/https://doi.org/10.1016/j.compositesa.2019.105750

[9] Hezaveh, T., Moazami-Goudarzi, M., & Kazemi, A. (2021). Effects of GNP on the mechanical properties and sliding wear of WC-10wt%Co cemented carbide. *Ceramics International*, 47(13), 18020-18029. https://doi.org/https://doi.org/10.1016/j.ceramint.2021.03.117

[10] Tao, J., Wang, X., Wang, Z., & Zeng, Q. (2019). Graphene nanoplatelets as an effective additive to tune the microstructures and piezoresistive properties of cement-based composites. *Construction and Building Materials*, 209, 665-678. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2019.03.173

[11] Meng, W., & Khayat, K. H. (2016). Mechanical properties of ultra-high-performance concrete enhanced with graphite nanoplatelets and carbon nanofibers. *Composites Part B: Engineering*, 107, 113-122. https://doi.org/https://doi.org/10.1016/j.compositesb.2016.09.069

[12] Chuah, S., Pan, Z., Sanjayan, J. G., Wang, C. M., & Duan, W. H. (2014). Nano reinforced cement and concrete composites and new perspective from graphene oxide. *Construction and Building Materials*, 73, 113-124. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2014.09.040

[13] Pershin, V., Mashhadani, Ali., Melekhin, D., & Osipov, A. (2020). Improving functional and environmental performance of Portland cement-based materials by graphene nanostructures. *MATEC Web Conf*, 315. https://doi.org/10.1051/matecconf/202031506006

[14] James, S., Fredrick, R. R., & Carnot, N. (2020). Shear Strength of Bonded Concrete. *Structures Congress*. https://ascelibrary-org.eu1.proxy.openathens.net/doi/epdf/10.1061/9780784482896.038

[15] Jacintho, A. E. P. G. d. A., Cavaliere, I. S. G., Pimentel, L. L., & Forti, N. C. S. (2020). Modulus and Strength of Concretes with Alternative Materials. Materials, 13(19), 4378. https://www.mdpi.com/1996-1944/13/19/4378

[16] Abedi, M., Fangueiro, R., & Correia, A. G. (2021). Development of a Novel Multifunctional Cementitious-Based Geocomposite by the Contribution of CNT and GNP. *Nanomaterials*, 11(4), 961. https://www.mdpi.com/2079-4991/11/4/961

[17] Mypati, S., Sellathurai, A., Kontopoulou, M., Docoslis, A., & Barz, D. P. J. (2021). High concentration graphene nanoplatelet dispersions in water stabilized by graphene oxide. Carbon, 174, 581-593. https://doi.org/https://doi.org/10.1016/j.carbon.2020.12.068

[18] Wu, S., Qureshi, T., & Wang, G. (2021). Application of Graphene in Fiber-Reinforced Cementitious Composites: A Review. Energies, 14(15), 4614. https://www.mdpi.com/1996-1073/14/15/4614

[19] Czarnecki, L., Gerylo, R., & Kuczynski, K. (2020). Concrete Repair Durability. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7600629/

[20] Saleem, H., Zaidi, S. J., & Alnuaimi, N. A. (2021). Recent Advancements in the Nanomaterial Application in Concrete and Its Ecological Impact. Materials, 14(21), 6387. https://www.mdpi.com/1996-1944/14/21/6387