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An Experimental Investigation of Environmentally Friendly Concrete Reinforced With Graphene Nanoplatelets

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Abstract **-** Carbon Dioxide (CO_2) is the principal greenhouse gas that contributes to increasing the greenhouse effect, which has a significant adverse impact on the environment. There are large quantities of carbon dioxide emissions associated with cement production. Production of cement is estimated to be responsible for approximately 8% of global greenhouse gas emissions. Besides its environmental impact, concrete also exhibits low tensile and ductility, which can result in cracks. In recent years, carbon nanomaterials, such as Carbon Nanotubes (CNT), Carbon Nanofibers (CNFs), Graphene Nanoplatelets (GNPs), Graphene Oxide (GO), and Reduced Graphene Oxide (rGO), have gained increasing attention from the building industry and scientific community due to their exceptional mechanical and physical properties. In fact, the use of carbon nanomaterials is considered an environmentally friendly method of enhancing the mechanical properties of concrete. The purpose of this study is to investigate the effects of GNPs on the mechanical properties of concrete using the wet dispersion method. In addition to using ultrasonic treatment to prepare GNP dispersions, a superplasticizer is also used to facilitate the dispersion of GNPs in water. Concrete specimens were prepared with 0.25 wt% GNPs. Compressive, flexural and tensile strength of concrete at age of 7 days were assessed. As a result of adding GNPs, strength of concrete specimens was enhanced. Furthermore, when GNPs were incorporated into concrete specimens, compressive, flexural and tensile strength was increased by 19, 8.7 and 9.1 % respectively.

Keywords**:** Compressive strength, flexural strength, Graphene Nanoplatelets (GNPs), nanomaterials, tensile strength, ultrasonic treatment, and wet dispersion.

1. Introduction

growth of many nations. However, the building industry has a significant environmental impact, which is due to the fact that during the production of cement a huge amount of Carbon Dioxide (CO_2) is immitted into the atmosphere. Cement production consists of four major stages. The first stage of the process involves grinding, crushing, and mixing limestone, clay, and other raw materials to create a blended mixture with a specific composition. During the second stage, the combined mixture is placed in a rotatory kiln. A gradual increase in temperature takes place inside the kiln until 1400 ˚C are reached in this second stage. As the temperature of the raw materials in the mixture increases, several chemical reactions occur. Initially, evaporation of free water occurs between 70˚C and 100˚C. Then chemical reactions between the limestone and other raw materials occurs between 450 ˚C and 1350 ˚C. When the temperature is between 1350 ˚C to 1700 ˚C, clinkers are formed. This second stage is the most energy-intensive in the cement manufacturing process, in which a massive amount of CO_2 is released as a by-product of burning the blended mixture. Additionally, in this second stage, lime (CaO) is produced by the calcination of limestone (CaCO3), releasing a huge amount of CO_2. In the third stage, the clinkers are cooled. The cooled clinkers are ground into smaller particles or fine powder. Powdered gypsum is included in cement as a retardant to control the setting time. The finished product is Portland cement, which is subsequently stacked and packed. This whole process of cement production contributes to about 8 % of global carbon emissions [1-3]. Additionally, concrete is brittle and therefore has low tensile strength and deformation capacity, resulting in low toughness. By improving the mechanical properties of concrete with advanced technologies and novel materials, in particular nanomaterials, it may be possible to reduce cement consumption.

In previous studies, many forms of carbon nanomaterials have been investigated and considered to be used as reinforcements in concrete, including carbon nanotubes (CNTs) [4], carbon nanofibers (CNFs) [5], graphene nanoplatelets (GNPs) [6, 7], graphene oxide (GO) [8] and reduced graphene oxide (rGO) [9]. Among those carbon nanomaterials, GNPs have the greatest economic potential. A graphene nanoparticle is composed of a small number of graphene sheets stacked on top of each other. These sheets possess the same properties as individual graphene sheets. Moreover, a single graphene sheet has outstanding properties such as tensile strength of ~130 GPa [9], and Young's modulus around 1 TPa [10]. A number of studies have demonstrated that GNPs enhance the mechanical properties of concrete, mortar, and paste cement. For instance, Wang et al. (2016) [7] added 0.05 wt % GNPs to cement paste specimens. They found that the addition of GNPs increased the compressive and flexural strength of cement paste by 7.5% and 23.7% at 7 days. They also reported that the inclusion of GNPs increased compressive strength and flexural strength by 3% and 16.8 % at 28 days, respectively. In the study of Francesca et al. (2021) [11], mortar specimens were prepared with 0.01 wt%. They found that GNPs resulted in improving compressive and flexural strength by 14% and 4% at 28 days, respectively. Additionally, in some studies the effect of adding different concentrations of GNPs to cement composites has been evaluated. For instance, in the study of Chen et al. (2019) [12], GNPs in concentrations of 0.02 wt%, 0.05 wt%, 0.1 wt%, 0.2 wt%, and 0.3 wt% GNPs was added to concrete specimens. They found that the compressive strength was enhanced by by 18.61%, 22.40%, 19.78%, 8.84%, and 1.42%, respectively. Arslan et al. (2022) [13] prepared concrete specimens with the inclusion 0,035 wt%, 0.07 wt%, 0.14 wt%, 0.21 wt%, 0.35 wt%, 0.70 wt% GNPs. They found that adding 0.14%GNPs resulted in the maximum improvement in mechanical properties. Indeed, the addition of 0.14 wt% GNPs resulted in improving compressive and flexural strength by 24% and 96%, respectively. From the literature review was found that the influence of GNPs on compressive and flexural strength varied in previous studies. In this study, the effect of GNPs on mechanical properties of concrete specimens is investigated. For this purpose, GNPs are incorporated into concrete specimens, then compressive and flexural strength is calculated at 7 and 28 days. For the incorporation of GNPs, GNP dispersions are prepared using ultrasonic treatment in combination with superplasticiser.

2. Materials

In this study, as a blinder material, Ordinary Portland Cement (OPC) was used to prepare concrete specimens. Crushed granite with maximum size of 20 mm was used as coarse aggregate. Washed sand was used as fine aggregate. Mixture proportions for concrete specimens are: cement 1, washed sand 2, coarse aggregate 5.05, and water 0.60. Fine and coarse aggregates are showed in Figure 1.

Figure 1. Fine and coarse aggregates, a) sand, b) 7mm, 14 mm and 20 mm.

3. Mixing Procedure and Preparation of Specimens

3.1. Preparation of GNP Dispersion

GNPs were dispersed in water using sonication treatment and superplasticiser (SP). 0.25% GNPs and 0.8% SP were added to water and then dispersed using a drill for 5 minutes. After this, the dispersion of GNPs was ultrasonicated for 20 minutes. An ultrasonic probe with a power output of 500 W was used in this study. The probe frequency of the sonicator was 20 kHz. The Sonication process was conducted at intervals of 2.5 minutes in order to prevent the increase in the temperature of the dispersion. Additionally, to avoid segregation of the GNPs, every 2.5 minutes when the sonication process was stopped, and GNP dispersion was mixed using a drill. The procedure for the preparation of the GNP dispersion is showed in Figure 2.

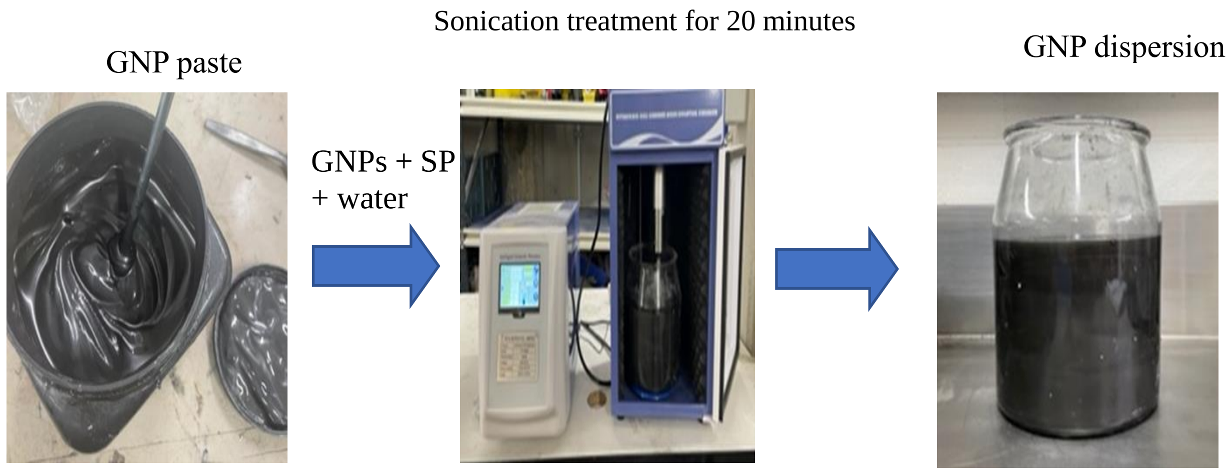

Figure 2. Procedure for the preparation of dispersion prepared with GNPs

For the preparation of the concrete specimens. Cement, sand and coarse aggregates were added to a drum mixer and mixed for 5 mins. Then, the GNP dispersion was incorporated into the drum mixer, and all concrete ingredients and GNPs was mixed for 30 minutes. A schematic representation of the procedure used for casting concrete specimens with GNPs is displayed in Figure 3.

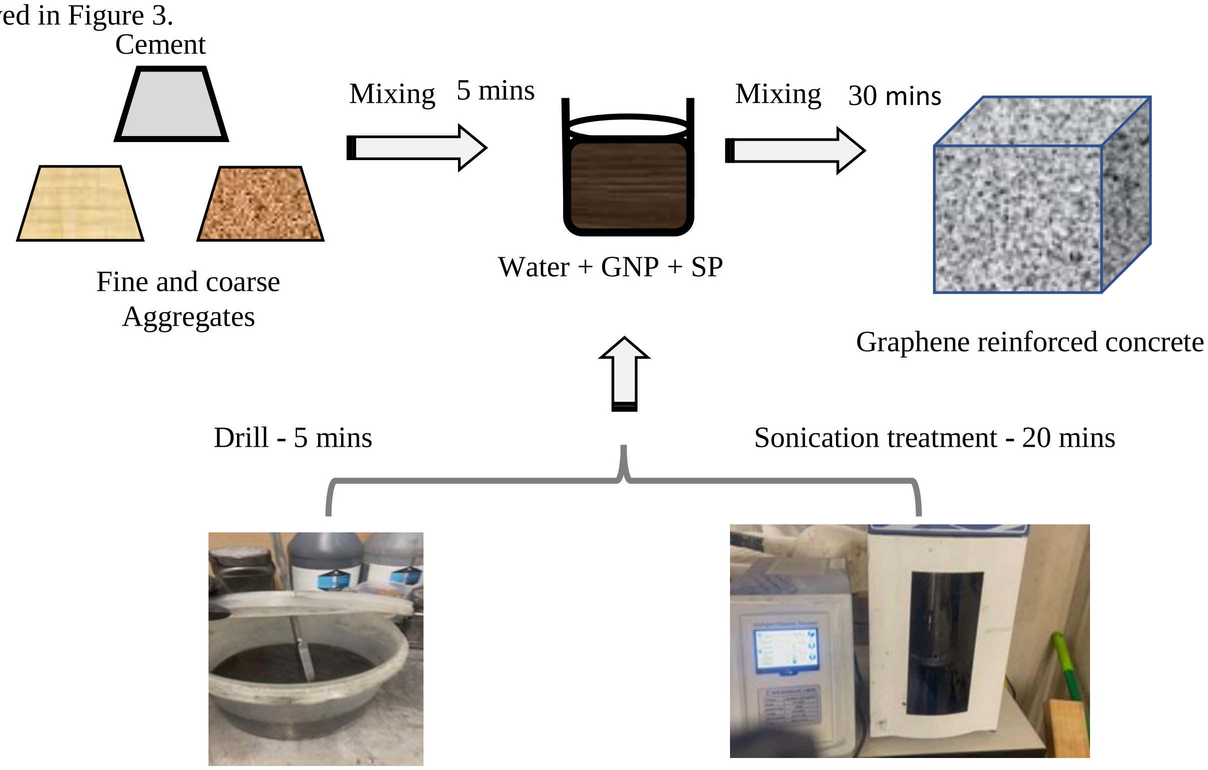

Figure 3. Procedure for casting concrete specimens with GNPs

4. Testing Methods

4.1 Mechanical properties.

Cylindrical concrete specimens with a diameter of 100 mm and a length of 200 mm were prepared for testing compressive and tensile strength. The compressive and tensile strength is determined in accordance with AS 1012.8:2014 and AS 1012.10.182. Prismatic concrete specimens with a cross-sectional area of 75X75 mm and a length of 290 mm were prepared for evaluating the flexural strength. Flexural strength was determined in accordance with the ASTM C293. For each test, five concrete specimens were prepared and tested after 7- days curing time. The set-up of strength tests and concrete specimens are showed in Figure 4.

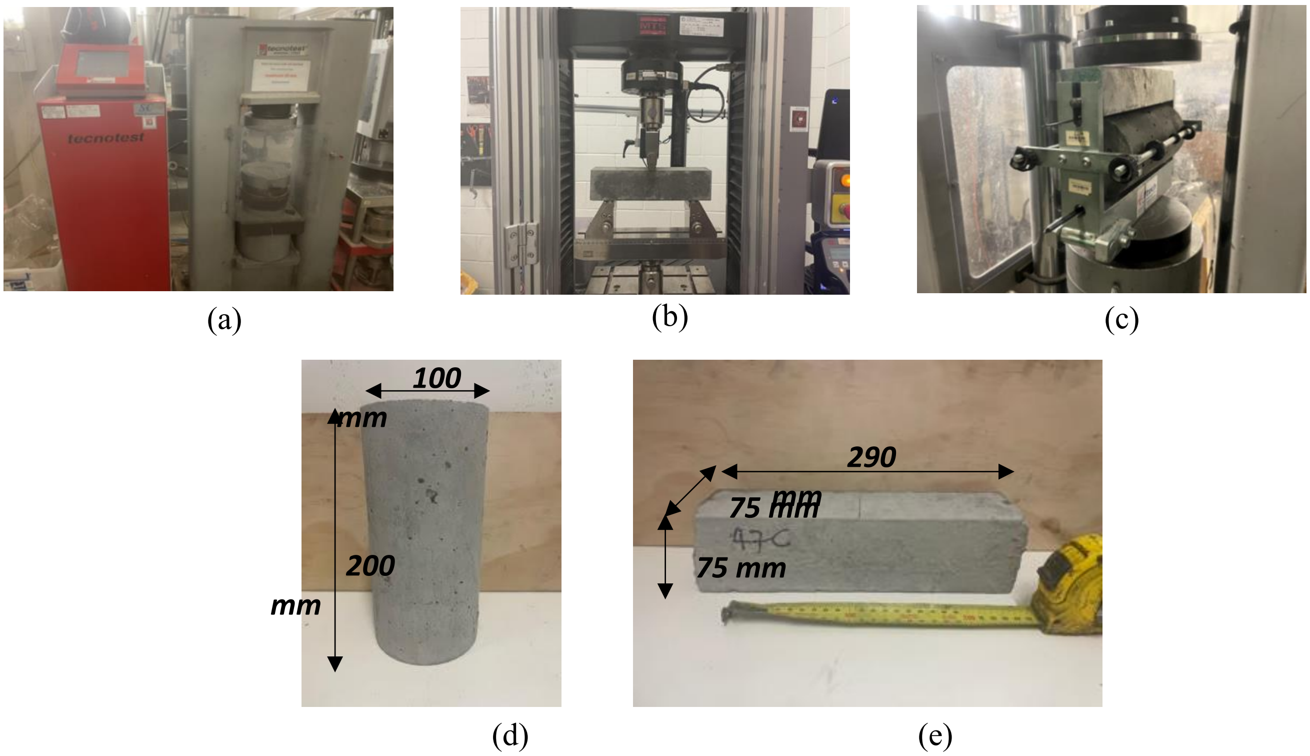

Figure 4. Set-up of strength test, a) compressive, b) flexural and c) tensile strength. Dimensions of specimens, d) compressive and tensile strength, and e) flexural strength.

Results and Conclusions

5.1 Results of mechanical properties

5.1.1 Compressive, flexural and tensile strength

The variation of the compressive, flexural and tensile strength of control and GNP concrete specimens at 7 days are presented in Figure 4. As it can be seen from the results, the addition of GNPs resulted in an improvement in compressive, flexural and tensile strength at 7 days. Moreover, the compressive strength was reported to be increased from 22.50 to 26.78 MPa at 7 days, representing an improvement of 19% with respect to plain concrete specimens. While flexural strength was slightly increased from 3.33 MPa to 3.62 MPa at 7 days, which is a slight improvement of 8.7% with respect to plain concrete. In addition, tensile strength increased from 2.30 to 2.51 MPa, which was slight improvement of 9.1% with respect to plain concrete. The improvement in compressive, flexural and tensile strength may be due to the reinforcement of the microstructure of the cement matrix. Indeed, the improvement of the microstructure of the cement matrix of concrete may be achieved by GNPs due to their ability to improve the interfacial bond between graphene nanoparticles and C-S-H gels [14, 15], and to mitigate crack formation and propagation [7, 16].

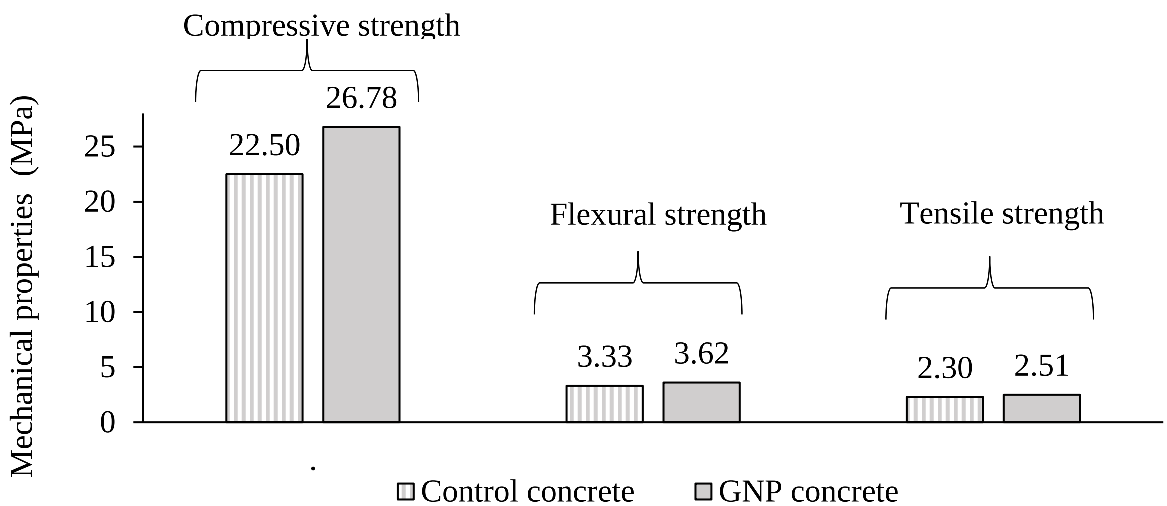

Figure 4. Compressive and flexural strength of control and GNP concrete specimens.

Previous studies have also found that the addition of GNPs can result in enhancing the strength of concrete specimens. Previous studies have shown that adding GNPs increased compressive strength of cement paste, mortar and concrete specimens. A comparison of the results of this study with those of previous studies is presented in Figure 5. It can be observed from the Figure 5 that the enhancement in compressive strength of cement paste, mortar and concrete specimens prepared with GNPs varied in previous studies. For instance, Chen et at. [12], incorporated GNPs to concrete specimens. They reported that the addition of 0.05 wt% GNPs caused an increase in compressive strength of 22.4%, with respect to control specimens. Wang et al. (2019) [17] prepared cement paste specimens with 0.06 wt% GNPs. They found that compressive strength of cement paste specimens was enhanced by 11.1 and 11.2, at 7 and 28 days, respectively. From the can be observed that in overall, cement composites prepared with GNP content ranging from 0 to 0.3 wt% may result in improving compressive strength. However, it can be also seen that when the GNP content is higher than 0.3 wt% GNP, the compressive strength of cement composites is negatively affected. These results can be explained that the fact that when GNPs is added in high concentration, the nanoparticles tend to agglomerate causing defects in the cement matrix, thus reducing the compressive strength of cement specimens [12, 18].

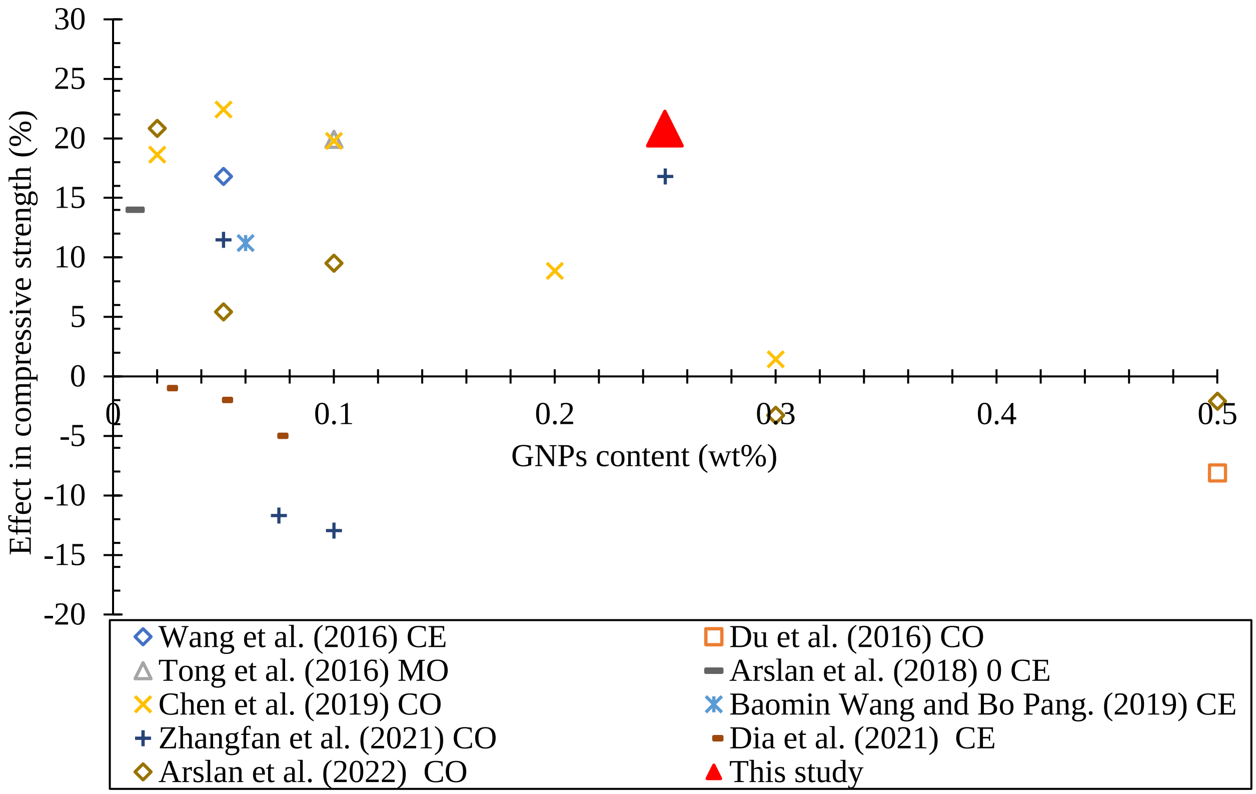

Figure 5. Effects of compressive strength of literature review vs this study. CE: Cement specimens, MO: Mortar specimens, CO: concrete specimens

Additionally, previous studies have also found that the addition of GNPs can result in enhancing the flexural strength of cement composites. A comparison of the results of this study with those of previous studies is presented in Figure 6. In the study of Zhangfan et al. (2021) [19] and Francesca et al. (2021) [11] was found that adding GNPs to mortar specimens slightly increased flexural strength. Zhangfan et al. (2021) [19] found that the addition of 0.075 wt% slightly increased flexural strength by 5.7%. While Francesca et al. (2021) [11] reported a slightly increase of 5.2 when 0.01 wt% GNPs were added. Additionally, Dia et al. (2021) [20] found that the addition of 0.025, 0.05 and 0.075 resulted in increasing flexural strength of cement pastes at 28 days by 14, 15 and 21%, respectively. In terms of concrete specimens, Arslan et al. (2022) [13] reported that the addition of small amount of GNPs (less than 0.35 wt%) increased flexural strength of concrete specimens. However, when the amount of GNPs was higher than 0.35 wt% they reported that flexural strength was adversely affected. Similar to compressive strength, the reduction of the flexural strength may be due to the agglomeration of GNPs which caused defect in the cement matrix of the concrete specimens [13, 19].

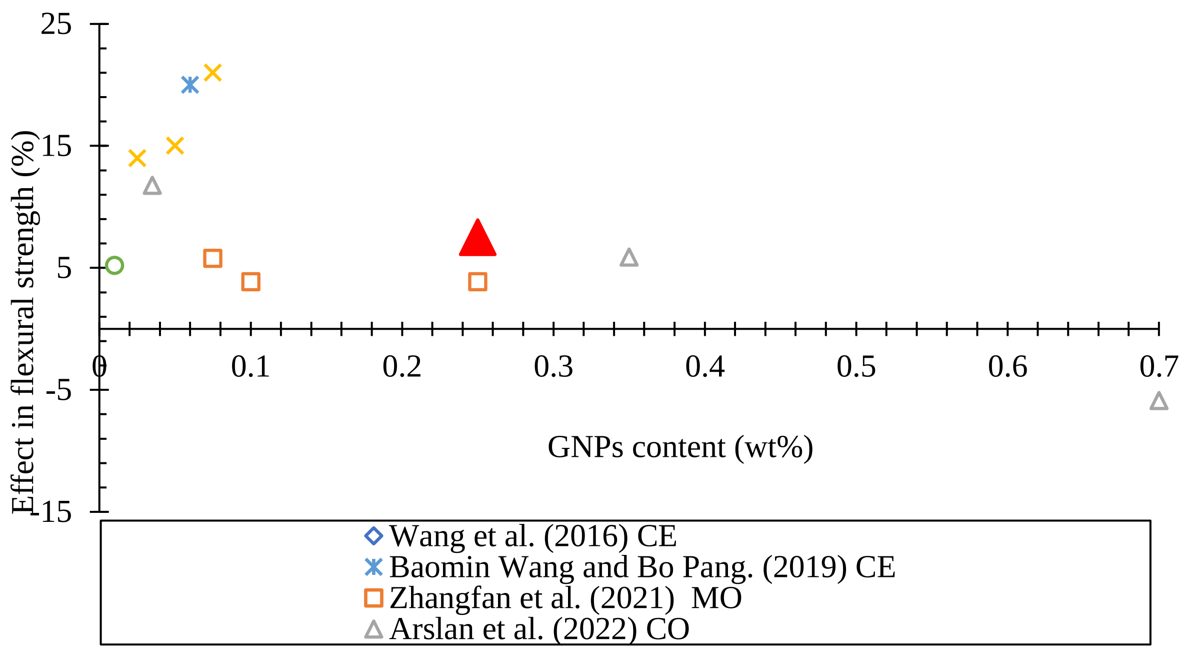

Figure 6. Effects of flexural strength of literature review vs this study. CE: Cement specimens, MO: Mortar specimens, CO: concrete specimens

6. Conclusions

Overall, the present results showed that GNP can be used in concrete to improve its mechanical properties. It was observed that compressive, flexural and tensile strength was improved by adding GNPs. Moreover, compressive, flexural and tensile strength was enhanced by 19, 8.7 and 9.1 %, respectively when 0.25 wt% GNPs were added. The improvement in mechanical properties may be attributed to the strengthening of the microstructure of the cement matrix. When compared these findings with those reported in previous studies, it was observed that the effect of GNPs on cement pastes, mortar and concrete are slightly different. This is due to various factors: i) properties of GNPs, ii) the amount of GNPs, iii) dispersion and mixing methods.

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