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Mechanical Property Enhancement of Cement Mortar via TiO2 Reinforcement: Experimental Investigation and Analysis

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***Abstract*—Energy efficiency and utilization in housing developments are two issues that the construction industry is becoming increasingly concerned about. Furthermore, the handling of solid glass debris that is not biodegradable is turning into a major global concern. For this reason, adding recycled expanded glass aggregates (EGA) to cement composites in place of fine aggregate from nature would be a sustainable way to reduce waste and construction energy usage. The purpose of this field experiment is to look at how EGA affects the thermal insulating capabilities of cement mortar as well as its fresh and solidified qualities. Nano titanium dioxide (nTiO2) was utilized as a nanofiller to improve the EGA-mortar's mechanical characteristics and water resistance. The EGA-mortar's workability and water absorption increased, according to the results. Additionally, adding EGA to the cement mortar resulted in a notable drop in bulk density and compressive strength. The EGA-mortar demonstrated superior thermal insulation qualities and a low rate of heat transfer. Additionally, the addition of nTiO2 improved the EGA-mortar's water resistance and compressive strength, but it additionally improved the rate of heat transmission. The findings showed that, in order to lower the energy consumption of residential structures, EGA-mortar may be used into the building envelope or non-load bearing components such wall partitions as a thermal resistance.**

Index Terms—Nano titanium dioxide, expanded glass aggregates, and nanofiller.

I. INTRODUCTION

Over the past several decades, there has been an increase in the need for electrical power in residential structures, and there is a strong desire to reduce this consumption. As energy costs rise and the public's understanding of the impacts of global warming grows, the energy efficiency of buildings has become more and more important. Moreover, waste management has developed into a crucial problem. In actuality, non-biodegradable trash like glass cannot naturally decompose, which is causing environmental issues. About 1.1 Mt of glass garbage were produced in Australia between 2016 and 2017, of which 43% were hoarded. Businesses in New South Wales that choose to transport their glass trash to state where the landfill tax is not applicable, or that accept the landfill fee in order to dispose of their garbage in a landfill [1]. Scientists continue to dig for breakthroughs in the rapidly expanding field of nanotechnology, which involves a variety of various industries such as building. Nevertheless, due to its strength and affordability, concrete is the most often used building material in the world. 2019 saw the production of almost 4.2 billion tonnes of cement due to the annual increase in demand [2]. The question of how to improve the structure's stability while making it has become more resilient, safe, and economical remains a challenge for scientists and engineers.

In addition, concrete lacked tensile strength and is fragile, while having superior compressive strength, durability, and stiffness. It is significant to remember that the same materials have distinct characteristics at the nanoscale compared to the microscale [3]. Various concrete varieties are created by adjusting the mix design, building method, and application location, as well as by considering market demands. By adding nanoparticles, some of the main drawbacks of concrete such as its high porosity and low hydration—can be mitigated. However, doing so will change the characteristics of the material.

For example, pores, which make up 2-6% of the concrete's overall volume, cause the substance's rigidity and durability to deteriorate with time. Consequently, the employment of nanoparticles to plug these detrimental holes will counteract the deterioration of concrete's strength and longevity. This hybrid impact of nano-silica, nano-alumina, and nano-titanium dioxide on the mechanical, rheological, and longevity properties of self-compacting mortar using fly ash as an addition was studied by a scholar. The findings show that, when applied alone, along with the nanoparticles nano-alumina, nanosilica, and nanotitanium dioxide, respectively, 1%, 3%, and 5% of the binder provided the greatest compressive strength [4].

The potency rose for this combo, peaking on day 90. Joshaghani made an additional attempt to combine nanoparticles, substituting carbon nanofibers (CNF) and nanotitanium dioxide for some of the cement. As a result, adding nanoparticles to concrete in place of some of the cement might help it develop its pore structure and become stronger and more durable. They also performed an inverted flow test to assess the effectiveness of CNF and nano-TiO2 in slump retention [5].

To examine the pore structure, tests for loss of volume, bulk resistivity to electricity, and durability against freezing and thawing were also carried out. Nazari and Riahi discovered that by substituting 3% of the cement with nano-titanium dioxide, the first hydration stage in the cement's formation is sped up, resulting in faster hydration and the production of C-S-H. On the other hand, this same team also noted that if nano-TiO_2 was added in excess of 3%, negative outcomes occurred. This resulted from the uneven dispersion of nanoparticles in the final concrete matrix and the reduction in the growth of $Ca(OH)_2$ crystals, which were necessary for the creation of C-S-H gel during the hydration process [6].

When concrete is exposed to sunlight, Nano-TiOTM may remove contaminants from its surface and cleanse it by simultaneously converting toxic gases like nitrous oxides and volatile organic compounds into less toxic byproducts. When cement and nano-TiO_2 are combined, photocatalytic activity is sparked, which may remove organic pollutants from road pavement surfaces and eventually lower air pollution [8]. In a different study, Nazari discovered that when applied to self-compacting concrete, nano-TiO_2 fills the pores and produces a stronger micro-structure. Additionally, he proved that when these additions account for 4% of the cement weight, self-compacting concrete exhibits improved splitting-tensile and flexural strength. Additionally, as was previously mentioned, this particular form of concrete reached a threshold of diminishing returns when the additives added to the mix topped 4% of the total weight of the cement [7].

The rest of the work is organized as follows: the literature survey is reviewed in section 2 followed by the materials and methods in section 3. The result and discussion is explained in section 4. The work is concluded in section 5.

II. RELATED WORKS:

Raza et al. [9] created GMR mixes, four distinct NTD doses were tested, ranging from 1 to 4% by the weight of the mix. Additionally, a consistent dosage of micro carbon fibre (CF) (0.5% by weight of the mix) was used. Additionally, a reference mix containing 0.5% micro-CF without any NTD dose was produced. Using scanning electron microscopy (SEM), the internal structure of GMR was evaluated. The various characteristics of GMR pastes were ascertained by averaging the results of six specimens from each paste. The findings of this study showed that the best results for hardness, impact strength, and compressive stress in a carbon-FR-GMR mix were obtained with 3% NTD, while the best results for the flexural stress and breaking strength of pastes were obtained with 2% NTD.

Yousefi et al. [10] suggested on experiment is to examine how EGA affects the characteristics of cement mortar—both fresh and hardened—as well as its ability to insulate against heat. Nano titanium dioxide (nTiO2) was used as a nanofiller to improve the EGA-mortar's mechanical characteristics and water resistance. The EGA-mortar's workability and water absorption increased, according to the findings. In addition, adding EGA to the cement mortar resulted in a significant reduction in bulk density and compressive strength. The EGA-mortar demonstrated superior thermal insulation qualities and a low rate of heat transfer. Additionally, the addition of nTiO2 improved the EGA-mortar's water resistance and compressive strength, but it also accelerated the rate of heat transfer. The findings showed that, in order to lower the energy consumption of residential structures, EGA-mortar may be used into the building envelope or non-load bearing components such wall partitions as a thermal resistance.

Keshavarzian et al. [11] stated an Taguchi technique to assess the impact of seven parameters on the attributes. In order to meet this criteria, 171 prismatic and cubic samples were made and put through testing for flexural, splitting tensile, and compression strength. The studies were then planned using Taguchi's experimental design technique in order to determine the ideal mechanical strengths of the SFRRPC. Taguchi and analysis of variance (ANOVA) techniques were used to evaluate the laboratory data. The values of mix proportions that maximised the mechanical strengths of SFRRPC were found. The optimal compressive, splitting tensile, and flexural strengths of SFRRPC were determined by 155.3 MPa, 8.3 MPa, and 53.9 MPa, respectively, based on the verification findings. The findings indicated that the most important components influencing the mechanical characteristics of SFRRPC were cementitious elements, such as cement and micro-silica. Additionally, the findings of the SEM test demonstrated that NS particles may improve the mechanical characteristics of SFRRPC by increasing the amount of C-S-H gels and filling the gaps in the microstructure. The addition of NS caused cementitious materials to hydrate to a high degree while reducing the CH content, according to XRD examination.

Li et al. [12] finded that the addition of NT may significantly improve the compressive strength of cement-based composites after 28 days of curing, resulting in an increase of 18.50% or 18.42 MPa and 6.41% or 6.38 MPa, respectively. Both sizes of NT may enhance the polymerization degree and average silicate chain length of $[SiO4]4-$ in C–S–H. Additionally, they have the ability to reduce the CH orientations, limit the CH size, and provide cement-based composites with a denser microstructure. Therefore, the flexural strengths and the ratios of flexural strength to compressive strength of cement-based composites that were cured for 3 days and 28 days have seen a notable rise. According to the nucleation free energy theory, the 10 nm NT has a higher number of nucleating sites compared to the 15 nm NT. Additionally, the energy required for nucleation at each nucleating point is lower for the 10 nm NT than for the 15 nm NT. Thus, the presence of 10 nm nanoparticles leads to a more significant nucleation impact compared to 15 nm nanoparticles. Additionally, the 10 nm nanoparticles have a superior enhancing effect on the mechanical properties of cement-based composites, as compared to the 15 nm nanoparticles, at equivalent levels and curing time.

III. MATERIALS AND METHODS

The research used ordinary Portland cement (OPC), natural aggregate (NA), recycled expanded glass aggregate (EGA), superplasticizer (SP), and nano titanium dioxide (nTiO2) as the ingredients for fabricating the cement mortar composite. The binder used in the mix was OPC from Boral Australia Co., which adhered to AS3972 standards. The superplasticizer (SP) utilised was Sikament NN, which met all the criteria specified in AS1478.1 for a high range water lowering admixture. The figure 1 displays EGA, provided by EGT Co., with a particle size ranging from 0.25 to 4 mm. EGA's requirements adhere to the EN and DIN standards. The figure 2 displays a scanning electron microscope (SEM) picture of the EGA (experimental gas analyzer) used in this work. The table1 presents the physical, mechanical, and thermal characteristics of the EGA.

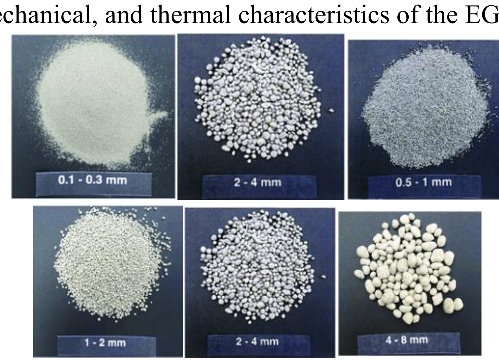

Fig 1: Different grain sizes EGA

The aggregate used as natural aggregate (NA) was crushed gravel with a maximum size of 4.0 mm and a density of 2800 kg/m3. The particle size distribution test was conducted on the NA to accurately reproduce the distribution of NA used for replacing EGA by volume in the cement mortar [13].

Table 1: Features of EGA (thermal, physical and mechanic)

Characteristics	Size of grain				
	0.25 to 0.5	0.5 to 1	1 to 2	2 to 4	4 to 8
Particle density (kg/m^3)	540	440	340	300	280

Thermal Conductivity (W/mK)	0.07	0.07	0.07	0.07	0.07
Loose Bulk Density (kg/m^3)	310	240	210	180	160
Compressive strength (MPa)	>2.8	>2.7	>2.5	>2.3	>2.1

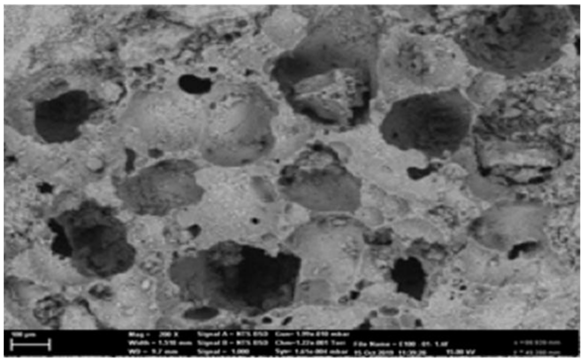

Fig 2: EGA's SEM structure

3.2 Designing the concrete mix

In this work we used M30 Grade concrete mix using the ACI 211.1-91 mixing protocols. The concrete mix consisted of a water-to-cement ratio of 0.51 and a set dosage of super-plasticizer of 0.3%. It is important to mention that the experiment maintained a consistent amount of both fine and coarse aggregate for the cement in all the samples. Prior to doing laboratory tests, the researcher used two different combinations of substances in different ratios, as shown in Table 2.

Table 2: Mixing proportion

	Quantity (kg/m^3)	Ratio
Fine aggregate	757	2.14
Water	180	0.51
Cement	354	1
Coarse aggregate	987	2.78

The term "CC" signifies the use of traditional concrete made from fine and coarse aggregate cement, whereas the acronym "NTAC" refers to concrete that includes nano-TiO_2 and nano-Al_2O_3 additions. In order to closely monitor and regulate the effects of partially substituting cement, nano-TiO_2 and nano-Al_2O_3 were introduced in a proportionate manner ranging from 0.5% to 2% for each sample. In order to determine the optimal percentage of nano-TiO_2 and nano-Al_2O_3, the experiment used a total of 12 combinations with varying quantities [14]. To guarantee a strong dataset, the experiment included three samples for each combination, resulting in a total of 39 samples. This dataset consisted of ordinary concrete and included three additional "CC" samples, making a total of three samples per 12 combinations with varied proportions. We allocated a unique code to each combination and sample to facilitate identification, as seen in Table 3 below. Prior to conducting a final comparison between the nano-concretes and conventional concrete in each combination, the mechanical parameters of each concrete sample, including compressive, split tensile and flexural strength, were examined.

Table 3: Concrete Mixing proportion

Code	W/C	CA (kg/m^3)	Nano-TiO_2 (%)	FA (kg/m^3)	Cement (kg/m^3)	Nano-Al_2O_2(%)
NTAC 01	0.51	986	0.5	758	349.45	0.5
NTAC 02	0.51	986	1	758	347.72	0.5
NTAC 03	0.51	986	0.5	758	347.72	1
NTAC 04	0.51	986	1	758	345.93	1
NTAC 05	0.51	986	0.5	758	345.93	1.5
NTAC 06	0.51	986	1	758	344.17	1.5
NTAC 07	0.51	986	1.5	758	344.17	1
NTAC 08	0.51	986	1.5	758	345.93	0.5
NTAC 09	0.51	986	2	758	342.42	1
NTAC 10	0.51	986	1	758	342.42	2
NTAC 11	0.51	986	2	758	340.64	1.5
NTAC 12	0.51	986	1.5	758	340.64	2
CC	0.51	986	0	758	354	0

3.3 Procedure followed for mixing

Initially, a combination of nano-Al_2O_3, nano-TiO_2, and super-plasticizer was meticulously blended with water for duration of three to five minutes using a high-speed stirrer. The experiment used a super-plasticizer to prevent agglomeration, enhance workability, and facilitate even dispersion, taking advantage of the cohesive properties of nano-particles. Once both the nano-particles and concrete mixture are prepared, the nano-particles mixture is put slowly into the rotary mixer. The whole combination of nano-particles was devoured in this manner until it was well blended with the concrete mixture. The specimens were fabricated and subjected to controlled laboratory conditions for curing, following the guidelines outlined in ASTM C192 [15].

3.4 Testing

The flow table test was conducted on the newly prepared cement mortar samples in line with AS2701 to assess the functionality and consistency of the mixes. Furthermore, the density of the combination was evaluated using the density test as specified in AS2701. The water absorption test, done in accordance with AS1012.21, was used to evaluate the water penetration of the specimens at 28 days of age. The cube specimens of 70 mm × 70 mm × 70 mm were subjected to a compressive test in line with AS1012.9 at the ages of 7, 14, and 28 days. Three samples were examined for each test, and the average, together with the error bar, was provided.

This research assessed the thermal insulation characteristics and heat transfer rate of cement mortar that includes EGA by monitoring the distribution of surface temperatures using an infrared thermal imaging camera. To obtain uniform beginning temperature, specimens measuring 70 mm × 70 mm × 30 mm were made and stored at around 27 ◦C for a few hours. Subsequently, the samples underwent exposure to a heat source, and the infrared thermal camera (Testo 872, Testo Australia) was used to record the surface temperature distribution on the opposite side for duration of 15 minutes. The heat test was conducted three times for each sample. Figure 3 depicts a schematic representation representing the thermal test.

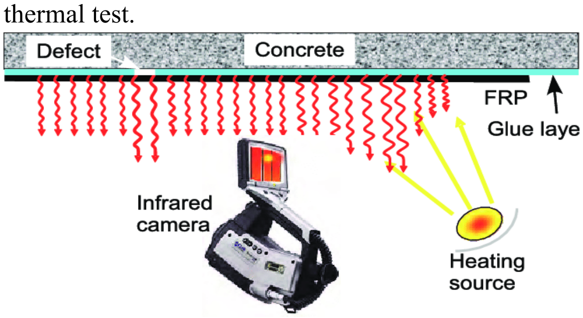

Fig 3: Thermal Testing framework

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IV. RESULTS AND DISCUSSION

4.1 Workability

The flow table test results were calculated by taking the average of the diameters obtained from each test of the different blends and are displayed in table 4. All mixtures exhibited flow values ranging from 140 to 215 mm, with no signs of segregation or bleeding. The findings indicated that the inclusion of EGA resulted to a significant improvement in the workability of cement mortar.

Table 4: Mixtures Flow diagram

Code	Mean Diameter of flow
NTAC 01	140.1
NTAC 02	170.23
NTAC 03	134.78
NTAC 04	156.67
NTAC 05	178.3
NTAC 06	139.03
NTAC 07	189.3
NTAC 08	201.4
NTAC 09	210.34
NTAC 10	199
NTAC 11	176
NTAC 12	218.7
CC	132.6

4.1 Splitting Tensile strength

The split-tensile strength values of the control specimen, as well as those of the concrete samples with varied concentrations of nano-particles, are displayed in Figure 4. Figure 4 demonstrates that the split-tensile strength increased when nano-particles were added, reaching its highest value at the optimal dose. The control specimen exhibited a strength of 3.42MPa, but the hybrid specimen had a strength of 4.58 MPa. This value was determined by averaging the results of three experiments with nano-Al_2O_3 and nano-TiO_2 content of 0.5% and 1%, respectively. Figure 4 illustrates a significant enhancement, namely a 34% boost in strength relative to the CC specimen after 28 days of curing. Therefore, it can be deduced that the incorporation of nano-Al_2O_3 and nano-TiO_2 into concrete mixes enhanced the tensile strength. The presence of nano-particles, particularly nano-TiO_2, with their extensive surface area, facilitates pozzolanic processes leading to the production of C-S-H gel and an overall enhancement in strength.

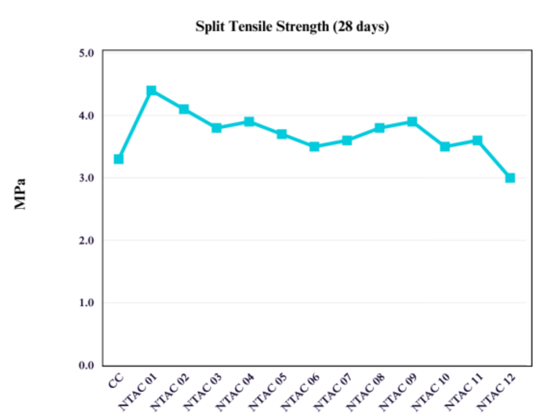

Fig 4: Analyzing the splitting tensile strength after 28 days (post curing)

4.2 Compressive Strength

The specified compressive strength, as determined by the mix design, was established at 30MPa, as recommended by the mix design. The optimal concentration of nano-Al_2O_3 and nano-TiO_2 was determined to be 0.5% and 1%, respectively, and this finding is associated with sample NTAC-02. According to the data shown in Figure 5, the compressive strength of the CC sample was 28.5MPa after the 28-day curing period. This value is 11.97MPa lower than the average compressive strength of the three NTAC-02 samples, which is 40.47MPa. The increase in question may be attributed to the involvement of nano-TiO_2 and nano-Al_2O_3 in the pozzolanic reaction. This results in a higher absorption of $Ca(OH)_2$, leading to an accelerated hydration process and the formation of C-S-H. Nanoparticles impede the motion of unbound water vapour inside the concrete, resulting in a filling effect. Figure 5 validates that the compressive strength of the material rose when nano-Al_2O_3 and nano-TiO_2 were used as 0.5% and 1% replacements for cement, respectively. However, the compressive strength dropped for larger percentages than the optimal dose, as seen in Figure 5. The negative impact is caused by the decrease or absence of Ca $(OH)_2$ crystals necessary for the formation of C-S-H gel and the uneven distribution of nano-particles inside the concrete structure. In addition, it was observed that samples with especially high dosages of nano-TiO_2, which have a wide surface area, exhibited a significant increase in water absorption.

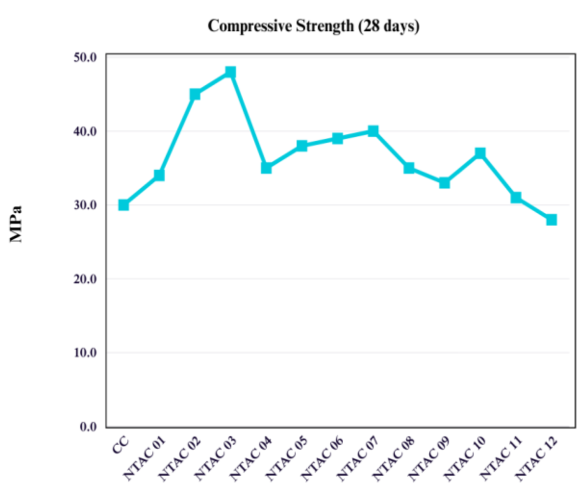

Fig 5: Analyzing the Compressive strength after 28 days (post curing)

4.3 Flexural strength

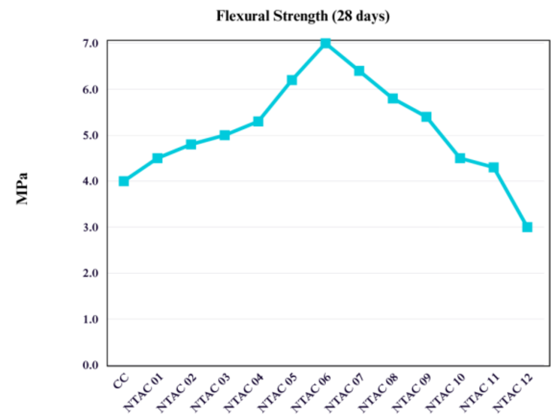

Fig 6: Analyzing the Flexural strength after 28 days (post curing)

The addition of nano-particles resulted in a substantial improvement in flexural strength. The flexural strength of the control item was measured to be 4.56MPa, whereas the NTAC-02 sample had a value of 5.84MPa, as shown in Figure 6. The outcome was a 28% increase in strength compared to conventional concrete compositions

V. CONCLUSION

This work examined the physical characteristics and thermal insulation capability of cement mortar that includes EGA and TiO2. The results showed that the addition of EGA to the mortar composite resulted to a notable reduction in both density and compressive strength. This may be ascribed to the porous characteristics and low compressive strength of EGA. The findings also indicated that when the EGA content rose, there was an increase in the workability and water absorption of the cement composite. The higher water absorption may be attributed to the greater porosity of EGA compared to NA. Nevertheless, the EGA had a positive impact by reducing the pace at which heat is transferred in the cement composite. This suggests that it is possible to potentially lower energy usage in buildings. Furthermore, the findings indicated that including TiO2 into the cement composite somewhat mitigated the effects of water absorption and reduced compressive strength. However, it was shown that the inclusion of nTiO2 in EGA-cement composites enhanced the rate at which heat is transferred inside the cement matrix and improved its insulating qualities. This is because nTiO2 functions as nanofillers and alters the structure of the pores in the cement matrix. Based on thermal behaviour, substituting NA with EGA reduces the rate of heat transfer and hence enhances the thermal insulation qualities of the cement mortar.

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