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Investigation of Nano-Composite Dampers Using Different Nanomaterials in Civil Engineering Structures: A Review †

Sandhya. R. Jalgar [1,*], Anand M. Hunashyal [1], Roopa A. Kuri [1], Madhumati. S. Dhaduti [2] and Shridhar N. Mathad [3]

[1] School of Civil Engineering, KLE Technological University, Hubballi 580031, Karnataka, India; amhunashyal@kletech.ac.in (A.M.H.); roopa.kuri@kletech.ac.in (R.A.K.)
[2] Department of Civil Engineering, KLE Institute of Technology, Hubballi 580030, Karnataka, India; madhumtisdhaduti@gmail.com
[3] Department of Engineering Physics, KLE Institute of Technology, Hubballi 580030, Karnataka, India; phyicssiddu@gmail.com
* Correspondence: jalgarsandhya@gmail.com

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Abstract: Civil engineering structures need to be protected from earthquakes, representing a new area of research that is growing continuously and very rapidly. Design engineers are always searching for lightweight, stronger, and stiffer materials to be applied as vibration-damping materials. Stability in dynamics necessitates an active, robust, and convenient mechanism that can absorb the kinetic energy of vibration to prevent the structural system from resonance. Recently, many researchers have successfully used nanomaterials to develop energy-absorbing materials that are lightweight and cost-effective. Traditional damping treatments are based on combinations of viscoelastic, elastomeric, magnetic, and piezoelectric materials. In this paper, a review of various damping techniques for composites made of cement modified by various nanomaterials like Nano $Al2O_3$ (Aluminum Dioxide), Nano SiO_2 (Silicon Dioxide), Nano TiO_2 (Titanium Dioxide), Graphene, and CNTs (Carbon Nanotubes) is presented. The designs of various nano-composite dampers are presented to strengthen the information progress in this field. The current study's goal is to discover how nanoparticles impact the cement-based material's damping properties. The study examined several nanomaterials in cement composites at differing concentrations. With the help of the Dynamic Mechanical Analysis (DMA) method and the Logarithmic Decrement approach, the damping properties of these composites were examined. Scanning Electron Microscopy (SEM) was used to examine the effects of nanomaterials on the microstructure and pore size distribution of the composite. Increasing the quantity of nanoparticles in cement paste may improve its capacity to lessen vibration. The experiments also showed that certain nanomaterials may improve load transmission inside the cement matrix and connect neighboring hydration products, helping to reduce energy loss during the loading process. These nanoparticles will eventually replace the large machinery employed to dampen vibrations in buildings due to their small weight, increased mechanical strength, and effective damping properties.

Keywords: dampers; vibration; viscoelasticity; kinetic energy; dynamic stability

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1. Introduction

Vibration reduction can be achieved by dividing methods into three categories: isolation of substructure, dissipation of passive energy, and design of the smart structure [1]. The passive energy dissipation method is the most promising since it is the most cost-effective and does not require any additional complicated devices to control or worry about failure in hazardous situations like typhoons. Usually, common materials used in structures are poor in reducing vibrations, and many non-structural materials like viscoelastic liquids, metal alloys, polymers, etc., are added to the system and positioned in crucial areas as essential parts to boost the system's overall damping capacity [2–6]. The capacity to dampen vibrations becomes increasingly important in today's trend of multistorey buildings, tall structures, and modern transportation systems to prevent hazards. Due to its reliance on mechanisms for energy loss or transformation, dampers with only high-amplitude dynamic load issues are partially addressed, particularly those caused by inadvertent earthquakes [7,8]. By improving the capacity of the cement matrix to passively absorb vibrational energy, damping can be improved to a certain extent [9]. The microstructure and individual component qualities have a major impact on the damping of composites made of cement and nanomaterials [10–13]. Neither the fundamental components nor the interfacial transition zone, such as the water–cement ratio, moisture content, type, and size of gravel, can be changed [14]. Flexural, longitudinal, and torsional damping terms are measured using various techniques, including the logarithmic decrement approach, the decaying sin wave method, the resonant frequency method, the semi-power method, and the duplicate rigidity method [14]. Equation (1) provides the relationships between major terms that are frequently used to calculate damping in cement–matrix composites:

$$2\varkappa = \aleph/2\pi = 2C/C_{cr} = \partial/\pi = \eta = \tan\theta = 1/Q \tag{1}$$

where

1. $\varkappa$ = ratio of damping, C = coefficient of viscous damping, C_{cr} = coefficient of critical damping
2. ∂ = non-dimensional logarithmic decrement, $\tan\theta$ = loss tangent where θ is the loss angle
3. η = non-dimensional factor of loss, Q = dimensionless resonance amplification or quality factor.

The current review paper aims to provide an overview of the most recent developments in damping behavior in cement matrix composites as well as various research findings and enhancement methods. The research explores the dissipation of the mechanical energy of cement-based materials in small-strain, low-frequency dynamic flexure, which is given by the loss modulus. It calculates the cement's constituents with and without admixtures, aggregates, and steel reinforcement, offering cement-based materials with up to 60% flexural energy dissipation. The fundamental principles for designing materials for energy dissipation and static performance are explained.

The existing work first focuses on the damping ability of various nanomaterials. Previous studies have explored different admixtures, polymers, silica fumes, reinforcements, etc., to increase energy-absorbing properties, but very few studies have been carried out reviewing the effects of various nanomaterials on the damping behavior of cement composites.

1.1. Damping

Dampers are developed and designed to safeguard structures, eliminate structural damages, if any, and prevent damage to residents by absorbing seismic energy and reducing structural distortions. Generally, dampers make the structure absorb energy and reduce harmful vibrations, forces, and accelerations to safeguard the structures and occupants. Many types of dampers are used: friction dampers, magnetic dampers, yielding dampers, and tuned mass dampers. Figure 1 depicts different types of damping.

Figure 1. Types of damping systems.

Internal Damping is brought about by the dissipation of mechanical energy in the material through microscopic processes. The damping brought about by the dissipation of mechanical energy from the relative motions between parts that share points of contact or support is also known as structural damping.

1.2. Damping Measurement

When attempting to investigate damping in a system, a model that will adequately describe the sort of mechanical energy dissipation in the system is selected [15]. There are two methods for calculating damping. The first uses a time-response record, whereas the second uses the frequency response method.

1.3. Damping Ratio

When creating and analyzing structures, the most frequently applied variable is the damping ratio, which plays a very important role. As a source of energy dissipation, it is also defined as the viscous damping mechanism. The equation below defines the system for a single degree of freedom (SDOF). Consequently, Equation (2) provides the damping ratio [16]:

$$\xi = \frac{c}{Cr} = \frac{c}{2m\omega} = \frac{c}{2\sqrt{mk}} = \frac{c}{4\pi mf} \tag{2}$$

where,

4. c = viscous damping coefficient, c_r = coefficient of critical damping of SDOF (single degree of freedom) structure, m = lumped mass, k = stiffness, ω = natural angular frequency, f = natural frequency.

1.3.1. Logarithmic Decrement

The best technique for determining vibration responses to free-decay, such as displacement, velocity, acceleration, and amplitudes, is logarithmic decrement. Equation (3) describes it [16]:

$$\delta = \mathbf{In}(\mathbf{yj})/(\mathbf{yj}+1) \tag{3}$$

where,

5. y_j = jth round of the cycle, y_{j+1} = (j + 1)th round of cycle.

1.3.2. Loss Tangent

The loss tangent is the product of the elastic modulas E and the loss modulus E″. Additionally, this parameter provides the stress–strain phase difference (ϕ) of concrete materials, as shown by Equation (4) [16]:

$$\eta = \tan\phi = \pi r^2 = \mathbf{E}''/\mathbf{E} \tag{4}$$

1.3.3. Equivalent Loss Factor

The damping capacity is the amount of maximal strain energy W to the dissipation energy per cycle ΔW. Equation (5) yields the comparable loss factor [16,17]:

$$\psi = \frac{Y}{2\pi} = 1/2\mathbf{\Delta W}/\mathbf{W} * \pi r^2 \tag{5}$$

2. Nanomaterials for Damping

2.1. Development of Nanomaterial-Based Concrete

This is a concrete that uses nanomaterials with nanoparticles of size less than 500 nm [18–21]. Nanoparticles act as super fillers in cement, making high-density concrete. Acting as binding agents is the main role of nanomaterials, which are smaller than the size of cement. This in turn improves the hydration gel structure. A new nanomaterial that accurately imitates the properties of silica fume has been designed; hence, nano-silica is one of the new technologies [22]. Since the discovery of nano-silica, many nanoparticles have been used in concrete, like CNTs, nano alumina, and titanium oxide, etc. [23–26].

2.1.1. Nano Alumina (nAl_2O_3)

Nano alumina acts as a dispersing agent in UHPC. Nano alumina's job is to fill in gaps in the hydration gel. Three samples were cast, totaling 58 specimens, that were then tested 28 days later to ascertain the alumina nanoparticles' effects on the cement composite's mechanical strength [27–30].

When nano alumina was doped into the cement matrix, the compressive strength of concrete cubes improved. When the amount of nano alumina in the composite was 1% by weight of the cement at 28 days, the compressive strength of the material increased by 33.14%. The addition of nano alumina resulted in enhanced compressive strength and a decrease in the duration of concrete's initial setting time. Microstructural analysis was performed using Energy Dispersive Spectroscopy (EDS) and SEM. It was observed that even the damping properties of the composite increased to a certain extent.

2.1.2. Nano Silica ($nSiO_2$)

As concrete has a low capacity to absorb energy, the methods that are used for vibration control need additional devices or instruments for the absorption of energy, but these techniques prove to be very expensive. The resistance of reinforced concrete structures to vibration is improved by adding some admixtures, as per the suggestions of recent studies. DDL Chung studied the addition of admixtures like silica fume, latex, methylcellulose, etc., to cement to enhance the damping capacity and increase the storage modulus [31–36]. Ke Goujon also stated that the addition of rubber powder and carboxylate SBR latex to concrete can increase the damping capacity by 30 to 90% by studying the damping ratios [37]. The method of cantilever-free vibration of the beam measures the ratio of damping. The coefficients that represent the damping properties are logarithmic decrement, loss factor, damping ratio, and Q factor.

Logarithmic Decrement δ

There is an important component called the optimal blending amount. If the optimum compounding amount is exceeded, the damping ratio will decrease. Adding Nano SiO_2 changes the size and position of the pores, resulting in the cement paste undergoing a microstructural change once the Nano SiO_2 is applied, resulting in a reduction in porosity and a reduction in pore radius. It has been noted that while nano concrete can become more compact with SiO_2, when additional content goes above a certain point, compactness decreases. Owing to their substantial specific surface area during the hydration process, nanomaterials require a lot of water, reducing the mobility of concrete and making it harder to form under specified water–cement ratios.

2.1.3. Nano Titania ($nTiO_2$)

Nano TiO_2 is very inert and acts as a filler. Due to its very small particle sizes, it aids in increasing strength and durability. Titanium dioxide TiO_2, being crystalline in nature, is available in three different forms: rutile, brookite, and anatase. Rutile and anatase are the most commonly used in construction as wide bandgap semiconductors that resist high temperatures [38–40]. We can combine TiO_2 with mortar or cement in two ways, by introducing a specific number of nanomaterials into the matrix and by coating the elements to protect them from the external environment. The first method is preferred to the second one.

In the first method, TiO_2 is added to water and mixed for a few. Cement and other aggregates are dry-mixed separately, then the water containing TiO_2 is poured into the cement–aggregate mixture and mixed properly. Fiber reinforcement is added to the matrix last and again, mixed thoroughly [41–43]. In the second method, to obtain a proper consistency, aggregates and other dry materials, including TiO_2, are dry-mixed together, and then water containing superplasticizer is added slowly and mixed for 3–5 min [44,45].

Titanium dioxide (TiO_2) nanoparticles are employed in the pore-filling effect in cement, and their high specific surface area speeds up the hydration process. In addition, TiO_2 has photocatalytic properties and thermal stability, making it superior. There is no pozzolanic activity seen in titanium dioxide, as indicated by several studies [46]. By restricting its growth space or promoting the quicker formation of CSH gels, TiO_2 nanoparticles reduced the size of CH crystals [46]. TG analysis was carried out on cement paste containing TiO_2 [46]. For self-compacted concrete, the maximum percentage of nano TiO_2 required is up to 4%. Higher flexural strength is seen when the percentage of nano TiO_2 is 3 wt.%. Available data indicate that 5% cement by weight gives the best results for durability testing. Higher percentages show improved performance, but the benefits are poor. By incorporating 1, 2, 3, and 4% TiO_2 as a cement substitute and 1, 2, 3, and 4% nano clay as a fine aggregate, this potential combination was investigated. The results that were achieved with 2% TiO_2 and 3% nano clay were an increase in compressive strength of 48.64% compared to the control, and a 21.83% increase over utilizing only 2.0% TiO_2 to modify concrete [47].

2.1.4. Carbon Nanotubes (CNTs)

Due to possessing marvelous properties like Young's modulus, tensile strength, high conductivity, and high specific area, carbon nanotubes (CNTs) are considered promising carbon nanomaterials. Up to 1000 m^2/g of specific surface area can be attained by a single carbon nanotube fiber with a fracture strain of up to 15% [48–50]. According to the available data, CNTs can be used as a strengthening element in cement matrices due to their pore-filling effect, good bonding, cross-linking effects, etc. [51–53], which can prevent cracks in concrete and contribute to higher damping properties. Dai and Liao [54,55] researched the damping properties of epoxy resin with CNT, which resulted in improved damping properties without undergoing large strains. There was a 56% improvement in loss tangent seen in the study by Tehrani et al. concerning the reference sample, while studying CNT-carbon fiber-reinforced epoxy composites. We can see that the polymer composites containing CNTs have attractive damping properties, as per the research to date.

A study on damping behavior was carried out in cement-based materials containing CNTs. In this study, various compositions of 0.033, 0.066, and 0.1 wt% MWCNTs were mixed into cement pastes and cured for 28 days, before testing the flexural strength of the samples. Logarithmic damping and DMA were used to study the damping properties of cementitious composites containing CNTs. To know the microstructural properties and porosity of the samples, SEM and Mercury Intrusion Porosimeter (MIP) instruments were used [56].

The loss factor and damping ratio was calculated to validate the damping properties of CNTs with cement composites. The damping ratio was found to express the level of damping, serving as an arithmetic mean. The loss factor is a useful constraint for evaluating the viscoelasticity and ability of a material to absorb energy [56]. With an increase in the content of MWCNT, the damping ratio was also seen to increase. The sample containing 0.1 weight percent of MWCNT had the highest observed CNT–cement composite damping ratio. After 28 days, an 18.3% improvement was seen, compared to pure cement paste [56]. Because the loss factor values in the cement composites with CNTs were larger than those of pure cement paste, it was established that the inclusion of MWCNT was able to boost the energy absorption capacity of cement paste [56]. Because of the friction between the MWCNT's large surface area and the cement matrix, the damping characteristics improved to a greater extent. Uniformly dispersed MWCNTs have large attractive forces with the cement matrix, helping bridge gaps [56]. The effect of edge bonding, as noted by Cinquin et al. [56] with the help of DMA, provides an accurate measurement of interfacial damping.

2.1.5. Graphene Oxide

Graphene oxide has been found to have an elastic modulus and tensile strength of approximately 32 GPa and 130 Mpa, respectively [57]. Its ability to produce large amounts of graphene oxide from cheap graphite powder has drawn interest in the majority of applications [57]. Graphene oxide has a very high surface area-to-volume ratio, so it can uniformly disperse more steadily in water than CNTs; hence, it is easy to modify properties like mechanical, rheological, and permeability. Introducing a very small quantity of graphene oxide, as low as 0.05 wt.%, increases compressive strength by 15–33% and flexural strength by 41–59% [57]. The water sorptivity and chloride penetration of graphene oxide-reinforced cement mortar have shown improvement [57].

3. Conclusions

In this review, the improvement in the damping behavior of cement composites with the addition of various nanomaterials has been reported, and the changes in properties have also been studied. This study also presents the theoretical as well as experimental aspects of the increment in damping characteristics. The addition of Nano SiO_2, graphene, MWCNTs, $Al2O_3$ nanoparticles, and Nano TiO_2 to the cement matrix can enhance the vibration–damping capacity. The damping ratio is increased to a greater extent when we add these nanomaterials. To achieve improved energy absorption capacities, determining the optimum quantity of these nanomaterials is essential.

Despite many limitations, the current investigation into the use of nanoparticles in concrete has revealed a number of benefits. Nanomaterials can increase mechanical strength, impact resistance, as well as long-term strength and durability due to their size in nanometers. The chemical composition of nanomaterials may also have an effect on other qualities, such as nano silica's capacity to convert calcium hydroxide into useful calcium-silica-hydrate gel, whereas nano alumina can speed up hydration. The strength of structures can be increased, and carbon nanotubes or carbon nanofibers can help with real-time structural health monitoring. Expertise and caution are required in nanomaterial construction since their use also poses health risks.

4. Future Scope

"There is plenty of room at the bottom", as Nobel Laureate Richard Feynman famously remarked in 1959 at the California Institute of Technology. There is a tremendous opportunity to use nanotechnology to enhance concrete for strong, innovative, and long-lasting projects. To see a significant difference with the use of nanomaterials in construction for an improvement in damping characteristics, tensile strength, compressive strength, flexural strength, impact strength, etc., in the future, the combination of nanoparticles with fibers should be studied, and this technology should be made more understandable, easy, and environmentally friendly.

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