IMPACT OF ENVIRONMENTAL FACTORS ON THE DURABILITY AND PERFORMANCE OF COMPOSITE MATERIALS

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Abstract
These Composite structures are increasingly being utilized in various industries due to their desirable mechanical properties, such as high strength-to-weight ratio and corrosion resistance. However, the behavior of composite structures under varying environmental conditions is a critical aspect that must be thoroughly investigated to ensure their long-term performance and durability. This review paper aims to provide a comprehensive overview of research conducted on the behavior of composite structures exposed to different environmental conditions, including temperature variations, moisture effects, and UV radiation. The paper discusses experimental, analytical, and numerical studies conducted to evaluate the influence of these environmental factors on the mechanical properties, structural integrity, and long-term performance of composite structures. The findings and key insights from the reviewed literature are summarized, and potential research directions and challenges in this field are also discussed.

KeyWords: Composite, structure, UV Radiation, Moisture Effect, Temperature, Chemicals, Environment.

Introduction

The environment is a major global concern nowadays due to the increasing rate of greenhouse gas emissions. Traditional metals, metal-based alloys or synthetic materials are usually responsible for emitting carbon dioxide (CO_2) gas during their processing and usage. In this context, researchers are interested in environment-friendly materials, such as bio-composites, and consider these as a possible replacement of metal and metal-based alloys or synthetic fiber composites. Bio-composites possess satisfactory mechanical properties, and are inexpensive, lightweight and structurally efficient materials. Alternatively, high-performance composites, where synthetic fibers, such as glass and carbon fibers are used, have a wide range of applicability from household to aerospace industries. However, recycling problem and their dependency on large volumes of fossil fuels for processing, generate environmental hazards on earth. The natural fiber composites are potentially environmentally superior to synthetic fiber i.e., glass reinforced composites in most applications, as the specific properties of the natural fiber composites are higher than those of glass in certain circumstances. Several mechanical properties of natural fiber composites could be compared with glass fiber composites. In addition, natural fiber composites are also the best choice for commercial purposes. Therefore, different interior parts and accessories are manufactured by natural fiber reinforced bio-composites in the production industries, especially in automotive, construction and packaging industries. However, bio-composites are mainly used for indoor applications due to their low durability and immediate degradation problem in the harsh and humid environment during outdoor usage. The lignocellulosic chemical composition and microstructure of the vegetable fibers are responsible for moisture absorption from the surrounding environment. This behavior causes weakening of the fiber-matrix bonding which might result in lower mechanical properties and poor dimensional stability. The highly hydrophilic nature of vegetable fibers and the moisture sensitivity of their composites are the main disadvantages in applying these composites for exterior usage. Therefore, it is important to consider the moisture absorption behavior of the bio-composites in moist and humid environments for their potential applications.

Advantages of Composite Materials:

Composites possess excellent strength properties while remaining lightweight. This characteristic is particularly advantageous in industries such as aerospace, automotive, and sports equipment, where weight reduction is critical for improved fuel efficiency and performance. Composite materials offer a wide range of properties that can be tailored to meet specific design requirements. By adjusting the type, orientation, and volume fraction of the reinforcement material, engineers can optimize characteristics such as strength, stiffness, and thermal conductivity. Many composite materials, especially those with polymer matrix systems, exhibit excellent resistance to corrosion and chemical degradation. This property makes composites suitable for applications in marine environments, chemical processing, and infrastructure exposed to harsh conditions. Composites can be molded into complex shapes, allowing for greater design freedom and the ability to create intricate structures with integrated functionalities. Composites often have superior fatigue resistance compared to traditional materials, such as metals. This characteristic ensures the durability and longevity of composite structures subjected to cyclic loading. Certain composite materials possess excellent electrical and thermal insulation properties, making them suitable for applications that require such characteristics, including electrical enclosures, circuit boards, and thermal barriers.

Intralaminar failure based continuum damage mechanics

Among the fiber and matrix damage that can take place within a lamina. However, in many damage investigations, only the intralaminar damage mechanism is modeled and the interlaminar damage mechanism is ignored or vice-versa without adequate justification. In this purpose, a user material VUMAT subroutine was compiled in FORTRAN code and implemented by the finite element explicit Abaqus software to characterize the intralaminar damage. To simulate the evolution of the damage, modelingmust take into account the various forms of damage occurring at the impact tests. It is not necessary that the numerical model take account all the physical phenomena observed if their presence does not affect in a relevant way the current turbine behavior. This choice was dictated by the infiltration of water in the presence of this type of damage and which can lead to the rapid degradation of the material due to aging effect.

Literature Review

Sedat Savas [2024] This study presents experimental and numerical investigations on the use of chemically untreated and recyclable hemp fibers as reinforcement for outer wrapping in reinforced concrete beams. Hemp fibers, recognized as an alternative to Carbon Fiber

Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP), were utilized in three forms: unwashed hemp, washed hemp, and hemp rope. The materials underwent distinct tensile tests, compression tests on cylinder specimens (15×30 cm), and 4-point bending tests on reinforced concrete beams (15×25×200 cm) wrapped with CFRP, GFRP, Glass Fiber Chopped Strand, Geotextile, and NFRP (Unwashed hemp, washed hemp, and hemp rope). Additionally, the epoxy used in wrapping underwent adhesive and tensile tests. Despite swelling during adhesion, untreated hemp demonstrated effectiveness in load-carrying capacity, positioning it as a viable alternative to costly petroleum-derived materials. A finite element model compared the experimental results, confirming the efficacy of untreated hemp fibers in reinforced concrete applications. This study contributes not only to the exploration of sustainable construction materials but also underscores the potential of untreated hemp fibers in meeting the demand for eco-conscious alternatives in structural reinforcement.

Quan Wang [2023] Plant fiber reinforced polymer matrix composites have attracted much attention in many industries due to their abundant resources, low cost, biodegradability, and lightweight properties. Compared with synthetic fibers, various plant fibers are easy to obtain and have different characteristics, making them a substitute for synthetic fiber composite materials. However, the aging phenomenon of composite materials has been a key issue that hinders development. In natural environments, moisture absorption performance leads to serious degradation of the mechanical properties of composite materials, which delays the use of composite materials in humid environments. Therefore, the effects of moisture absorption performance of plant fiber composite materials on their mechanical properties have been summarized in this article, as well as various treatment methods to reduce the water absorption of composite materials.

M. Nachtane [2018] Composite materials are used in many marine structures such as renewable marine energy conversion systems because of their fairly good mechanical properties and especially their low densities compared to traditional materials. The most advanced features currently available in finite element (FE) Abaqus/Explicit have been employed to simulate the behavior of the composite nozzle under hydrodynamic and impact loading. A hydrodynamic analysis was considered to design the nozzle turbine and the hydrodynamic pressure obtained was then implemented as boundary conditions to a FE code. The goal of this article is to evaluate the durability of composite materials of a ducted tidal turbine under critical loads (hydrodynamic and hydrostatic pressures) with the implementation of a failure criterion using the finite element analysis (FEA). The mechanical behavior was analyzed for two materials (Carbon–epoxy/ Glass–polyester). This has been accomplished by forming a user-created routine (VUMAT) and executing it in the ABAQUS software.

Gaston Francucci [2015] In this work, a novel treatment on plant fibers is presented and its effect on the mechanical properties and water absorption of vinyl ester matrix composites is analyzed. The treated fibers used in this study consisted in alkaline-treated jute fibers and alkaline-treated jute fibers coated with polyhydroxybutyrate (PHB). Bending tests and IZOD impact tests were performed to evaluate the mechanical performance of the composites. The samples were immersed in water (at room temperature and at 80°C) and the water sorption and flexural modulus were measured in time. Flexural strength and impact energy were measured on dry specimens and the detrimental effect of water on those properties was evaluated by testing the samples after the immersion tests. The composites manufactured with alkali-treated fibers coated with PHB showed the best performance in terms of water absorption and mechanical properties.

Min Zhi Rong [2015] The present paper investigates the effect of fiber treatment on the mechanical properties of unidirectional sisal-reinforced epoxy composites. Treatments including alkalization, acetylation, cyanoethylation, the use of silane coupling agent, and heating were carried out to modify the fiber surface and its internal structure. As indicated by infrared spectroscopy, X-ray diffraction and tensile tests, variations in composition, structure, dimensions, morphology and mechanical properties of the sisal fibers can be induced by means of different modification methods.

Research Methodology

The thermal model that we propose lets us obtain the mass loss produced due to the polymer matrix decomposition and the temperature field through the thickness of laminated composite materials exposed to fire. Most of the models in the literature are developed on this principle. Our model is based on other quantities of interest, such as the thermal expansion, the porosity, the permeability, the stocked gases mass, and the internal pressure, which are not usually modeled or not evaluated in common models proposed by other authors. The mathematical model is developed for the case of unidirectional heat transfer in a polymer composite laminate and is based on the work published by Henderson and Wiecek. Certain assumptions must be introduced to simplify this model: Thermal exchanges between the decomposition gases and the solid material occur until thermal equilibrium; moreover, a decoupling of the composite fire is considered, which means the flame itself is not modeled. The latter is represented as a constant heat flux which is not modified by the thermal degradation of the material. The initiation and development of fire are not taken into account in the analysis. Moreover, the behavior of the decomposition gases is assumed to be ideal. The gas flow will be governed by Darcy’s law and the absence of reaction of the decomposition gases is supposed.

Results

FRESH CONCRETE

Slump Test

Slump cones are used to measure the “workability” or “consistency” of fresh concrete mix. The slump value for nano-composite specimens and conventional concrete specimens are shown in Figure When the slump value is increased then the workability of concrete also increased because the slump values are directly proportional to workability. On the other hand, when the slump value is decreased, the workability of concrete is very stiff. From Table. The conventional concrete specimen gives higher slump value and good workability when compared with the nano-composite concrete specimens. Subsequently, the mix B-1, B-2 and C-1 gives higher value and is equal to the mix C-2, D-1 and D-2 respectively. The workability of concrete is decreased in order to increase demand of water, due to the addition of nano materials, further decreased the slump value and shortened the initial and final setting time by increased colloidal nano-silica. Nano particles have higher surface area so that higher insist of water during the hydration time. Nano-SiO_2 when replaced with cement, to reduce the slump value due to nano particles have large surface area and absorb the more water molecules.

Table 1: Slump value in conventional and nano composite concrete Mixes

S.No.	Mix designation	Slump value in mm
1.	A -0	80
2.	B -1	75
3.	B -2	85
4.	C- 1	75
5.	C -2	70
6.	D -1	75
7.	D – 2	70

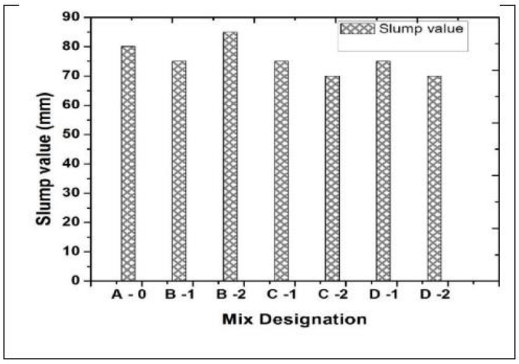

Figure 1: Variation of Slump values of control specimen and nano composite specimens

SCANNING ELECTRON MICROSCOPE (SEM)

The SEM is used to determine the particle size of nonmaterial and internal defects such as porous structure, air voids and density of concrete. Figure shows the microstructure of A-0 conventional concrete. Figure shows the dosages of 2% and 5% with the binary combination mix B-1, B-2. The combination C-1 shows the optimum dosage used the mixtures where the structure is very tight and void is less. C-2 mixes can be seen that bleeding of more calcium in hydration activity of cement. Figure shows ternary combination of mix D-1 and D-2, as there are more voids. Finally these microstructure views are used for easy identification of the strength and durability of concrete and mortar specimens.

SEM Test of Conventional Mix

Control concrete specimens (A-0) were studied using the SEM images as given in. Due to the sequential arrangements of cement and sand particles, many pores are observed in free concrete specimen. During initial curing period of concrete specimen, it is produced high intensity of vaterite peaks as shown in Figure. The concrete specimen obtained in this study gives good early age strength due to the calcium ions on the surface of the concrete specimens. Thus the calcite particles were precipitated directly and gradually on the surface of concrete as shown in Figure. Also CaCO3 particles were uniform in size and cemented to each other more tightly and giving evident protection to the surface of the specimen. The presence of considerable smaller amount of white CaCO3have been identified in the specimen. It could be seen that the CaCO3 particlescemented to each other and formed a layer on the surface of the concrete which effectively filled the capillary holes on the surface of the concrete specimen.

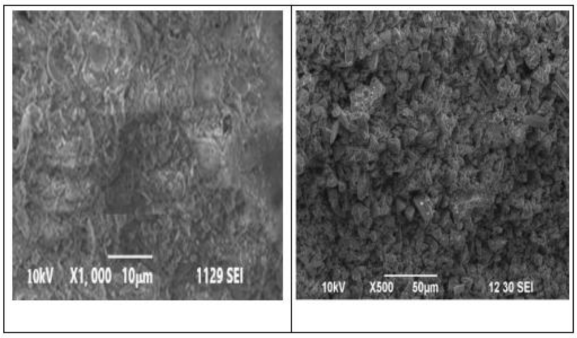

Figure 2 :SEM Image of Control concrete specimen (A - 0)

SEM Test of Binary Combination of Nano Composite Concrete

Specimen

Binary combination mixes such as B-1 mix (2% nano-SiO2+ 2% nano CaCO3),B-2 mix (5% nano-SiO2+ 5% nano CaCO3), C-1 mix (2% nano- SiO2 +2% nano-Ca(OH)2 and C-2 mix(5% nano-SiO2 +5% nano-Ca(OH)2) were studied using the SEM images as shown in Figures 4.3a to 4.3d. A clear calcite precipitation was found on the concrete specimens in the binary combination as shown in Figures. shows the calcite (in the form of CaCO3) in the specimens. The sample taken from the area which were close to the surface showed calcite crystals growing all over the sand particles. The SEM images indicated that CaCO3 crystals were precipitated on concrete specimen surface, where the sands were consolidated and cemented by CaCO3 crystals resulting in an increase in the compressive strength. On closer observation of the area containing dense calcite precipitation, it was found that the calcium carbonate crystals were well developed near the surface of the specimen. They had presence of distinct and sharp edges, indicating a full growth of calcite crystals. Interior area of the specimen showed high calcite precipitation with small amount of pores in the concrete specimen observed in the Mix C-2 mix (5 %nano Silica+5 % nano-Ca(OH)2 as shown in figure.

CONCLUSION

In conclusion, the investigation of the behaviour of composite structures under varying environmental conditions is a crucial area of research in structural engineering. This review paper has provided an overview of the literature on the subject, highlighting the effects of temperature variations, moisture, UV radiation, and chemical exposure on composite structures.

The findings from the reviewed studies demonstrate that environmental factors significantly influence the mechanical properties, structural integrity, and long-term performance of composite materials. Temperature fluctuations induce thermal stresses and can lead to delamination and reduced load-carrying capacity. Moisture absorption causes dimensional changes, microcracking, and degradation of composite structures. UV radiation exposure leads to photo-degradation and reduces stiffness, strength, and surface appearance. Chemical exposure in corrosive environments results in material degradation and loss of mechanical properties. The review has also identified several research gaps and areas for future investigation. These include the need to study the combined effects of multiple environmental factors, explore long-term durability, develop standardized testing protocols, advance monitoring and characterization techniques, investigate sustainable composite materials, and conduct field studies and case studies to validate laboratory findings.

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