Recent trends in Non Destructive Testing and Evaluation in Civil Engineering

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ABSTRACT

Non Destructive Testing (NDT) plays an important role not only in the quality control of the finish product, it also used for conditioning monitoring of various items during operation to predict and assess the remaining life of the component while retaining its structural integrity. Non-destructive testing, non-destructive evaluation, and non-destructive inspection are the terms represent the technique that are based on the application of physical principles employed for the purpose of determining the characteristics of materials or components or systems for detecting and assessing the in homogeneities and the harmful defects without impairing the usefulness of such materials or components or systems. This paper is representing a review of suitable NDT methods to assess civil structures and installations for any types of discontinuities that may appear in when the structures are in use at site. The main objective of this work is to explore about the useful NDT techniques that are now being used in modern industry. Through this study one can make idea about the recent trends in NDT evaluation.

Keywords- Non-Destructive Testing (NDT); Ultrasonic Pulse Velocity (UPV); Radiography, Reinforced Cement Concrete (RCC); Civil Structures

I. INTRODUCTION

Non-destructive testing is an essential practice within the field of material science and engineering that consists of an assortment of methods and techniques, which are used to inspect and assess the quality and integrity of materials, components and structures without causing damage to the said materials, components or structures. The objective of Non-Destructive Testing (NDT) and evaluation is to detect flaws, defects or irregularities on material surfaces or inside the material which may affect the structural integrity or negatively impact the functionality of the structure. By employing various NDT & E techniques, one can assess the internal and external conditions of the materials and accurately judge their suitability for the given task and if those require maintenance, repair or replacement. It is a rapidly evolving field which is playing a crucial role in ensuring the safety, reliability, cost-effectiveness and efficiency of various industrial sectors including manufacturing, infrastructure, energy, automotive and more. NDT has become indispensable in providing defect free, quality and reliable products.

NDT has been playing a crucial role in the domain of Civil engineering for quite a long time. Many different NDT practices are used to evaluate the health and integrity of a structure without damaging them. Different surface inspection methods like Visual Inspection, Dye Penetrant Tests, Magnetic Flux Methods, Eddy current tests etc. can be used to detect surface and sub-surface defects and irregularities [1] [2]. Figure 1 shows the application of dye penetrant test to detect surface and sub-surface cracks for a typical casting assembly. Other common NDT techniques like Radiographic Testing, Ultrasound Testing, Computer Tomography etc. are being successfully used to assess internal flaws and structural weaknesses of buildings, roads, bridges and other infrastructures [1] [3]. A typical test set up of ultrasonic testing is shown in Figure 2. This test can be done in workshops, labs and in site also. A recent trend in the field of NDT uses a technique that synthesizes acoustic data to analyze flaws and irregularities in structural elements and building materials such as, wood, concrete, steel etc. [4] Complex mathematical models and algorithms are used to process the data, which in turn gives us the idea of the structural integrity and damage in an efficient and comprehensive manner. X ray Computed Tomography, Ultrasonic Pulse Velocity Tests, Rebound hammer tests are some of the modern techniques being implemented in assessing the building materials and structures in the domain of civil engineering.

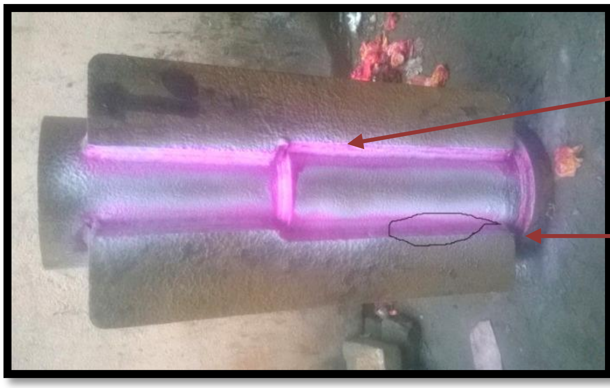

Figure 1: DP Test of hydraulic cylinder casing assembly
(Photograph taken by Satyabrata Podder) Courtesy: Test Metal Corporation, Kolkata

Another recent development in NDT is the growing usage of Micro Non-destructive testing and evaluation to assess micro features like porosity and damage in concrete cores in much bigger structures [5]. X-ray computed tomography, ultrasonic, radars and many more modern technologies are being used effectively for monitoring health, and providing quality and safe designs for large structures. In a totality, NDT has lot to do in the field of civil structure engineering. With the advent of new technology and existing demand with a variety of problems in the assessment of installed structures of various materials, presently scientists and engineers are exploring new methods of structural assessment without disturbing the normal functionalities. This is the true essence of NDT in the assessment of civil structures.

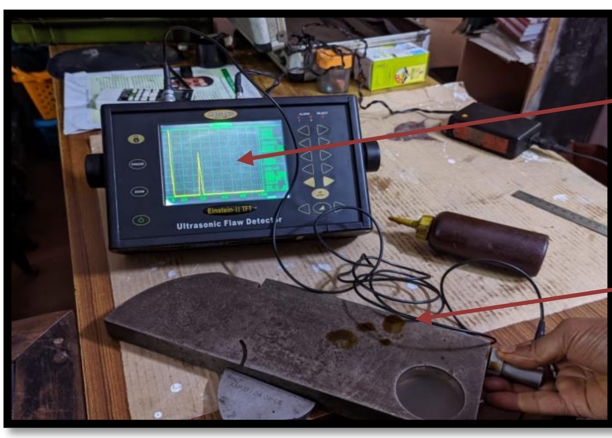

Figure 2- Calibration of ultrasonic testing machine with the help of IIW V1 block
(Photograph taken by Arka Dasgupta) Courtesy: Test Metal Corporation, Kolkata

II. NDT METHODS USED IN CIVIL ENGINEERING

There are several types of NDT techniques that are being used by researchers and engineers in the civil engineering field. Some of them are being used for a long time in the industry and they are called conventional NDT methods. Some of these methods are quite new, and modern technologies are being implemented to improve the process constantly. Researchers are working on making the older methods more reliable and overall better by integrating them with other technologies. New more efficient methods for testing civil engineering structures are being developed every day. Each of these conventional as well as advanced methods plays a functionally different role and sometimes their functionality overlaps with each other. These methods also have their own sets of advantages and limitations that can make them more or less suitable for testing a given structural member. Each type of job requires a different method or sometime multiple methods together to detect the flaws and irregularities effectively with better practicality. The most basic and widely used Non-Destructive Testing technique is Visual Inspection (V.I.) [6]. This is a visual optical method for testing an object for flaws and irregularities before other NDT methods which are more complicated in nature is applied. This process includes examination of the surface and external features like dimensions, surface flaws or irregularities of an object by touch and feels using rudimentary mechanical and optical aids and instruments. Even with the advent of new advanced NDT methods, VI is almost always the first step taken by the NDT inspector for evaluating conditions of civil engineering structures like roads, bridges, buildings etc. A modern non-contact, optical NDT method that is being actively developed is called Shearography [7]. This is used for detecting, measuring and analyzing surface and subsurface anomalies in a given test part under small amounts of controlled stress. Impact damage, de-bonding, delamination, near surface porosity, wrinkled fibers, fiber bridging, foreign objects, heat damage and cracks can be detected using a common path, laser-based imaging interferometer. This method is useful for testing large scale aerospace, naval and civil engineering structures, and can cover a large structure at a time using laser light sources, shearography cameras, and analyzing computers in a very time efficient manner as opposed to some of the more conventional NDT processes like Ultrasonic Testing (UT). Another conventional NDT process used for inspecting the internal structures of materials is called the Radiography Testing (RT). This popular method uses X-ray or gamma rays to detect defects and irregularities in various fields of engineering including manufacturing, construction and other related industries. Figure 3 shows few welding defects that can be revealed by RT in welded structures and frames. In recent times, researchers have developed a new software framework called 'virtual data fusion' to accurately detect cracks in concrete [8]. This framework was built using X-ray Computed Tomography (CT) images from different samples. This method shows a new path for reliable and accurate crack detection using cross verification of different XCT images and computed analysis.

Herringbone Porosity **Cluster Porosity** **Longitudinal Crack** **Elongated Slag Lines**

Figure 3- Radiography films of welded specimens showing different types of welding defects detected by RT (Photographs taken by Debashis Sarkar) Courtesy: Test Metal Corporation, Kolkata

Ultrasonic Testing (UT) has been a very popular choice for testing internal defects in materials for a long time. Ultrasonic waves are sounds waves having very high frequency (20 kHz) which can travel through different materials at different velocities [9] [10]. The ultrasonic waves propagate through materials in the form of longitudinal waves or shear waves. And at the interface of two different materials, some part of the wave reflects back and the other portion gets refracted. UT is a conventional NDT method, which uses the reflected ultrasonic waves to create images and detect internal defects. This method also gives the idea about the shape, size and location of the defects, and is widely used in various industries like aerospace, manufacturing and civil engineering. In recent times, computer modeling and numerical simulation are being integrated with ultrasonic testing to do better predictive analysis of the defects [11] [12]. Researchers are working on using Finite Element Modeling to study elastic properties and grain orientations of anisotropic austenitic stainless-steel welds [11]. This process is very helpful in optimizing the ultrasonic testing process. And also gives us ideas about quantitative features of the welds for the purpose of categorizing the welds based on their structures. Numerical simulations are also being used by researchers and engineers to determine parameters of Ultrasonic testing and analyze the results of the tests done on components [12]. The computer simulations provide the support to Ultrasonic testing and help in determining process parameters of the tests. Moreover these simulations can be used for doing predictive analysis of objects that has not been manufactures yet to see what kinds of defects and irregularities may occur to the test block. This modern NDT technique is proving to be very useful for monitoring structural health in many crucial industries like Nuclear power plants and other civil engineering structures.

Evaluating the structural health of concrete is one of the primary use of NDT techniques in the domain of civil engineering. Concrete structures can develop defects over time that threatens the integrity of the structure. These defects can develop due to cyclic loads and environmental exposure and can cause complete failure of the structure if left unchecked. Several NDT methods are used, and new methods are being developed every day for non-intrusive test such structures for defects and flaws that might not be apparent to the naked eye. Large concrete structures like bridges and buildings can be tested for strength using methods like Rebound Hammer Test and Ultrasonic Pulse Velocity Test [13]. Modern NDT tests like, i) Infrared thermographic technique, (ii) Acoustic Emission techniques, (iii) Short Pulse Radar methods, (iv) Stress wave propagation methods - pulse echo method, impact echo method, response method are used to test concrete structures for defects like cracks, voids etc. To evaluate corrosion damage of the reinforcements of such large civil structures can be tested using i) Half-cell potentiometer (ii) Resistively meter test (iii) Test for carbonation of concrete (iv) Test for chloride content of concrete (v) Profometer (vi) Micro covermeter etc. All these tests have their own advantages and limitations, and are used according to the specific use case in conjunction with each other. Poor quality concrete and damaged reinforcements of large civil engineering structures can be recognized and be rectified accordingly. Vibration Response Signal Analysis is another modern NDT technique being researched by scientists to detect local and analyze local damage and crack propagation in concrete beam structures [14]. New algorithms are being designed based on an unscented Kalman filter and successfully used with the vibration Response analysis results to identify structural damages and greatly reduce the computer workload efficiency over conventional methods.

A new method that is being successfully used by researchers for assessing damages of concrete structures is called stack imaging of spectral amplitudes based on impact echo (SIBIE) procedure [15]. This was used to visualize cracks and voids in concrete structures with the help of multiple sensor array composed of a handy mechanical device with accelerometers. 3D models of elastic wave propagation behavior were constructed using numerical algorithm and analyzed for laboratory specimens as well as a real life reinforced concrete structure. A predictive system has been developed by researchers which can estimate the occurrence of critical crack in concrete structures [16]. This method analyzes acoustic emission data and 3D sound spectra to detect micro events in concrete composites, which indicate the upcoming crack in the concrete. Acoustic emission tests are also proving to be very useful for analyzing adhesive-bonded Carbon Fiber Reinforced Plastics (CFRP) [17]. CFRPs and other composite materials are a widely used in aerospace applications and other related fields. These materials are attached with each other using adhesives, fasteners, or sometimes both. In laboratory conditions, different joint of these materials are analyzed under various mechanical tests. The acoustic emission data is then analyzed to better understand the strength and effectiveness of different joint in composite material structures. Another modern NDT method uses acoustoelastic effect to assess stress conditions in anisotropic materials [18]. The changes in the acoustic waves after interacting with the material are analyzed using numerical simulations and compared with the stresses measured from laboratory experiment. This has proven to give very reliable and accurate stress estimation method for weak anisotropic materials. Lately, Finite Element Method (FEM) has played a significant role in structural health monitoring (SHM) of civil structures and systems, like bridges, buildings and more. In this method complex systems are broken down into small, finite parts that are more manageable. Considering the interaction between these finite elements an approximate solution is given for systems, which are too complicated for other analytical methods. This modern technology has been successfully used to analyze the propagation of elastic waves in simple one-dimensional structures and studied to gain a better understanding of monitoring structural health of real-world complex systems [19]. New SHM technique is being worked on by researchers that use small, pressurized capillaries into a component [20]. This method helps detecting the fatigue cracks in these components. When a fatigue crack occurs and the capillary system is broken into, the crack results in loss of pressure in the capillary system, which can then be detected by a pressure sensor. This method is known as effective structural health monitoring (eSHM). It has been shown through experiment that introducing small capillaries (diameter 0.5 – 1 mm) has negligible effect on the fatigue crack propagation, and thus is an excellent method for detecting fatigue cracks in straight lugs. NDT tests are also being used to evaluate thermal stresses induced in large concrete structures. The temperatures of large concrete structures are not same in every part of the structure. Due to environmental exposure and other factor temperatures of the surface and internal portions of concrete are different. This induces thermal stresses which may be a cause of eventual damaging of the structure if not taken care of. Numerical models are being developed by researchers and engineers, that can help predict the temperature field in large structures like bridge decks [21]. This data is corroborated by experimental results and helps inspectors in minimizing the effect of thermal stresses on these civil structures. Therefore, it is observed that there are many NDT methods, which are currently being used in Civil engineering and even more modern sophisticated methods are being rapidly developed by researchers and engineers. The usage of NDT methods in the domain of civil engineering is broadening itself every-day and ensuring safe, sustainable structures around the globe.

III. APPLICATION OF NDT IN CIVIL ENGINEERING

The application of NDT techniques in the field of civil engineering has become a necessity in modern society. Proper utilisation of NDT provides more public safety, longer life span of new and aging infrastructure and ensures a more sustainable society as a whole. These methods help in evaluating the condition and defects in civil engineering structures without damaging them and have become indispensable in providing safe roads, bridges, buildings and other infrastructure and in turn contributing to a safe and healthy Infrastructure with a longer lifespan. One of the biggest applications of NDT methods in civil engineering is being used to monitor Reinforced Cement Concrete (RCC) structures [22]. RCC is widely used worldwide in various structural elements and infrastructure. Defects and irregularities of these RCC structures can be in successfully assessed by NDT. Durability of these RCC can be increased by testing the structures in various stages of construction. These tests are; 1) Pre-qualification tests, 2) Identity tests, 3) Quality assurance/Quality control tests, and lastly 4) In-place tests. Among these NDT tests are largely used during In-place tests, which ensures the standard quality and long term durability of RCC. Various NDT tests are also being used on existing RC elements to detect cracks and localization in large structures [23].

Reinforced concretes can develop cracks over time due to increased loads; environmental exposure etc., which in turn causes loss of strength and reduces the lifespan of these structures. Rebar Locators and Rebound Hammers (Figure 4) are very useful NDT methods that are being applied at site with ease. Ultrasonic Pulse Velocity (UPV) is another in-situ NDT method (Figure 5) to assess concrete quality and nature of rock. Presently, Fibre Optic Sensors (FOS), Acoustic Emission (AE) sensors are being widely used by researchers and engineers to monitor structural health of large infrastructures like walls, bridge decks and multi-story buildings. AE based detection of cracks using piezoelectric crystals produces excellent detection rate of individual cracks, but it falters in case of large areas due to high attenuation of ultrasonic waves. On the other hand FOS based setups can cover large areas efficiently but lags behind in locating the damage accurately. Researchers are working on a combined AE based FOS global system which can cover large infrastructure effectively without the shortcomings of previous systems. Concrete beams are being tested using this new approach under laboratory conditions applying Four-points bending tests until failure. These test results are then analyzed using numerical models and predictive models are being developed which lets us better understand the conditions of damage and failure of RC structures. These different testing methods integrated together are showing a true promise of a real-time structural health monitoring system. Non-destructive evaluations are also being used to detect corrosion damage in RCC structures [24]. A novel method is being researched which includes artificially inducing corrosion in test concrete specimens and monitor the damage using 3d imaging and automated NDE setups using multiple sensors and analyze the damage to do predictive monitoring in real world scenarios.

(a) **(b)**

Figure 4- (a) Rebar Locators are very useful to find out the position of steel reinforcement in concrete (b) Rebound Hammer test is very useful at site to measure compressive strength of concrete (Photographs taken by Satyabrata Podder) Courtesy: Duttcon Consultant and Engineers Pvt. Ltd. , Kolkata

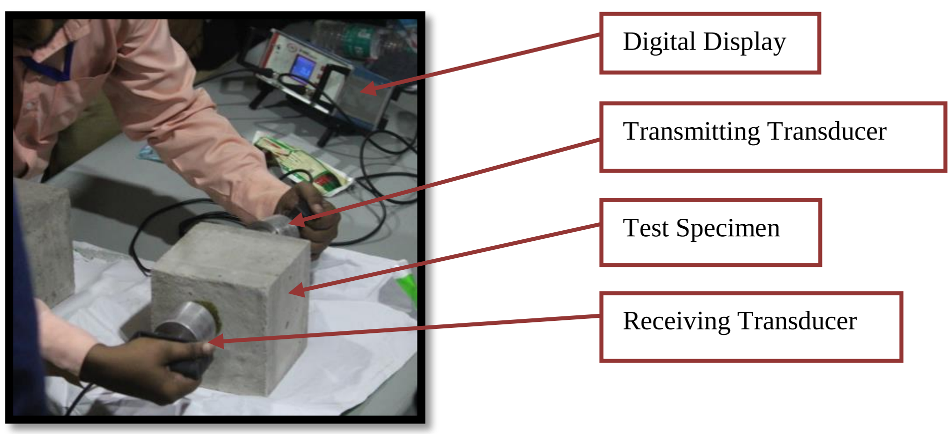

Figure-5 Ultrasonic Pulse Velocity Testing of Concrete (Photograph taken by Satyabrata Podder) Courtesy: Duttcon Consultant and Engineers Pvt. Ltd. , Kolkata

Damages in civil and mechanical structures can be identified by implementing a proper Structural Health Monitoring (SHM) system [25]. SHM is conducted in conjunction with condition monitoring, non-destructive evaluation, statistical process control (SPC) and damage prognosis to detect structural damages at the earliest possible time. One of the most useful applications of SHM is to monitor condition of existing bridges and highway system which are nearing their end of life cycle [26]. Non-destructive load tests and structural modelling is used to rate the load carrying capacity of such structures. An objective load rating system of such bridges can be developed by using LRFR method, Baseline enhanced designer models and Bridge Girder section loss model which can be compared with each other to effectively ensuring proper conditions and safer more sustainable bridges. In recent times bridge deflections are being monitored by researchers implementing interferometry, computer vision, digital image processing, a laser Doppler vibrometer, a Robotic Total Station, a GPS, and a video deflectometer [27]. The huge amount of data gathered on bridges under various static and dynamic load conditions using technologies like Terrestrial Laser Scanning (TLS), photogrammetry and tachymetry are analyzed to find the maximum bridge deflection conditions. NDT techniques are conducted periodically by engineers to monitor the progress of damages on the concrete members of the bridges over their lifespan [28]. This provides engineers with the information on structural health of the bridges and allows them to take preventive measures in case of loss of structural integrity. Researchers of the globe are working on implementing state of the art NDE techniques which include ultrasonic echo array, ground penetrating radar (GPR), active infrared thermography with induction heating, and time-resolved thermography with induction heating combined with 3D microwave imaging to detect damages which are then analyzed to take preventive measures accordingly. These modern techniques are breaking new bounds in helping efficiently managing resources while also providing safer bridges than ever before. Detailed 3D Finite Element Models (FEM) of highway bridges are being developed by engineers and researches by collecting huge amounts of field data using conventional and modern NDT methods [29].With the rapid advancement of software technology, instrumentation and data management it is being increasingly possible to develop detailed FEMs and in turn helping engineers take design decision on future bridge constructions. Instrumentation, Visual inspections and non-destructive load tests are being conducted on existing bridges and laboratories to construct a baseline finite element model. This helps in future to easily monitor the structural health of these bridges and also provides invaluable design guidelines for new bridges under construction. NDT evaluations and FEM and field management calculations have been done on the largest span soil-steel bridge in Europe to inspect and provide comprehensive, accurate analysis of the bridge deformations and comparing them with FEM computer model predictions [30].

In today’s time scientists and researchers are also working on the usage of NDT methods to evaluate and monitor health conditions on historical structures. Ultrasonic extensometry setups based on acoustoelastic (AE) effects are being used to evaluate true stresses in such structures [31]. The non-destructive methods using AE are being implemented to detect true stresses in historical masonry walls and then compared with destructive tests on similar walls under laboratory conditions. Degradation of stone structures are also being tested using NDT and impact tests by testing the columns of Via Crucis portico, within the monumental complex of the Sacro Monte in Ghiffa (Piedmont, Italy) [32]. These tests help evaluate the structural conditions and stability and provide possible maintenance information for degraded structuresGround Penetrating Radar (GPR) and Ultrasonic testing has been used to diagnose a historical floor in St. Nicholas’ Church, Gda´nsk, Poland [33]. These tests were conducted in conjunction to numerical model analysis to successfully detect anomalies in this structure. Thus NDT techniques are not only helping develop new, safer and more sustainable infrastructure but also pioneering new ways to monitor and preserve old, historical and heritage structures.

IV. ARTIFICIAL INTELLIGENCE ENABLED NDT IN CIVIL ENGINEERING

In today’s perspective the application of Artificial Intelligence (A.I.) has become an inherent part of modern technologies. NDT practices are not an exception to this. Artificial Intelligence is a collection of various technologies and tools that mimic human intelligence. Neural networks, deep learning, machine learning, data mining etc. are a few examples of A.I technologies. In the recent years researchers are exploring the possibility of the application of A.I. in NDT practices for predictive analysis and unsupervised learning of exploratory data analysis (EDA). Exploratory data is generated from the statistical graphics and data visualization.

Unmanned Aerial Vehicles (Drones) are used to capture scanned images along the predefined programmed motions to diagnose tall buildings and huge structures [34]. HD camera, infrared cameras, LIDAR, and 3D scanners are being used to capture data. The size and quantity of these data being very huge, it is not possible to find out damages and irregularities by a simple human attempt, as we do in visual inspection. Therefore a heuristic system is the demand of the modern time, which can be fulfilled by the application of Deep Learning. Deep Neural Network (DNN) algorithms are being used to analyse the scanned images to find irregularities. The Big Data Analysis is used to achieve the final output [35].

Conventional Neural Network (CNN) is also a popular choice [36] for the evaluation of surface cracks in concrete structures. Not only photographs or scanned images, presently deep learning is being used to analyze waveforms like sound and noise to measure surface strength of rocks [37]. This methodology is particularly very useful for the structural health monitoring of historic structures. Neural networks can also be used to analyze elastic waves to predict forces in bolted connections [38]. Bolted connections are important part of steel structures. Other than bolted connections, welded joints also can be analysed by the AI tools like Fuzzy Systems and Neural Networks [39].

Artificial Intelligence has made it possible to capture and analyse data for surface as well as internal irregularities with high accuracy and faster response time. In future days to come, we can expect a huge contribution of the learning algorithms and AI in the field of modern NDT practices. This will not only improve the efficiency of the existing processes but also will reduce time and human effort.

V. CONCLUSIONS

Non-Destructive Testing and Evaluation is an important segment of on-site testing and health assessment. In civil structures, historical monuments, bridges, flyovers, building etc. comes under the purview of NDT. The scope of NDT in civil structures is expanding with the advent of new technologies. This creates a new horizon of in-situ and on-site inspection. The present work is a review of few of the emerging NDT methods in the field of civil engineering. From the review following few points can be noted for future development.

a) Conventional NDT methods are being successfully used in the inspection.
b) Radiography and ultrasonic testing is very much suitable in the inspection of welded structures.
c) Apart from the existing methods, a prominent development in the field of visual inspection, radiography, acoustic emission, ultrasonic testing is observed in recent days.
d) There is an increasing trend is observed in the NDT of historical buildings and constructions.
e) Artificial Intelligence has got a lot of things to do in near future in the field of NDT overall.

Data Availability Statement: All data available in the paper.

Acknowledgement: Authors thankfully acknowledge the required permissions from Elitte College of Engineering, Kolkata and Techno Main, Salt Lake to do the research work for the review. Authors are also thankful for the permissions from Test Metal Corporation, Kolkata and Duttcon Consultant and Engineers Pvt. Ltd. Kolkata to use their testing equipment and take photographs in their laboratories.

Conflict of Interest: The authors declare no conflict of interest.

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