**SMART MATERIALS IN CONSTRUCTION**

Smart materials are a class of materials that can change their properties in response to external stimuli like temperature, light, stress, or magnetic fields. These materials have garnered significant interest in the field of civil engineering, due to their potential to improve the performance, durability, and efficiency of structures and infrastructure. With the advancement of technology and the researches, new materials have been the developed and new types of smart materials have been introduced. Here are some smart materials that have been explored in civil engineering.

**SHAPE MEMORY ALLOYS (SMAs)**

A shape-memory alloy denotes a type of metallic alloy that possesses the remarkable ability to return to its initial shape even after undergoing substantial deformation. Similar to how humans retain memories of acquired knowledge, significant life events, and even mundane details such as phone numbers, inanimate objects can also exhibit a form of memory. This memory is ingrained within the arrangement of atoms constituting these objects, which remains preserved indefinitely until external forces cause alterations. Ordinarily, once altered from their original state, these objects remain in their modified configuration. However, recent advancements in shape-memory technology enable objects to retain the recollection of their original shape and, upon exposure to heat, seamlessly restore themselves to that initial form. In the context of metal alloys, the phenomenon of shape memory empowers them to revert to their original shape.

The implications of this innovation are profound as it has paved the way for the creation of materials recognized for their exceptional durability. Dating back to the 1960s, these shape-memory alloys have found diverse applications across sectors such as medicine, robotics, aerospace, and automotive industries. Notably, the construction sector is now progressively embracing these materials, capitalizing on their manifold utility across various applications.

SMAs have the ability to return to a predetermined shape after being deformed. In civil engineering, these alloys can be used to create self-healing structures, adaptive structures that change shape in response to environmental conditions, and earthquake-resistant systems.

These materials exhibit the unique property of returning to their original shape or size when exposed to specific thermal changes. Within civil engineering, shape memory alloys find utility in novel projects aimed at bolstering the seismic resilience of structures. These alloys are particularly valuable for absorbing strain energy across multiple cycles without incurring permanent deformation. This capability enables them to display a broad spectrum of cyclic behavior, rendering them indispensable for enhancing fatigue resistance. Their adoption is attributed to their exceptional durability and long-term reliability.

Shape memory alloys possess a unique property characterized by two distinct crystal structures or phases. The specific phase exhibited by the shape memory alloy (SMA) is determined by both temperature and internal stresses. At lower temperatures, the SMA assumes the martensite phase, while at higher temperatures, it adopts the austenite phase. In the martensite form, the SMA can be easily manipulated into various shapes due to its malleability. However, upon heating, a transformation occurs, shifting the SMA from martensite to austenite. In the austenite phase, the memory metal effectively retains the original shape it held prior to deformation.

The relationship between stress and temperature is illustrated in the graph below, elucidating the behavior of martensite and austenite within the SMA. Specifically, martensite is dominant at lower stress and lower temperatures, whereas austenite becomes prominent at elevated temperatures and increased stress levels.

The most common memory metal is called NiTinol, consisting of equal parts of nickel and titanium.

**Table 1. Examples of Alloys having Shape Memory Effect**

|  |  |
| --- | --- |
| **Alloys** | **Transformation Temperature Range (Celsius)** |
| Ag - Cd | -190 to -50 |
| Au - Cd | 30 to 100 |
| Cu - Al - Ni | -140 to 100 |
| Cu - Sn | -120 to 30 |
| Cu - Zn | -180 to -10 |
| Cu - Zn - (Si,Sn,Al) | -180 to 200 |
| In - Ti | 60 to 100 |
| Ni - Al | -180 to 100 |
| Ni - Ti | -50 to 110 |
| Fe - Pt | approx. -130 |
| Mn - Cu | -250 to 180 |

The memory transfer temperature is the temperature that the memory metal or alloy changes back to the original shape that it was before deformation. This temperature can be very precise, within 1 or 2 degrees of the desired temperature.

**Properties of Shape-Memory Alloys**

Shape-memory alloys exhibit two distinctive traits. Firstly, upon heating, these alloys return to their initial shapes. Secondly, they display superelasticity, endowing them with the ability to endure significant strain and subsequently recover from it. These attributes hold immense significance for the construction sector. Furthermore, various types of shape-memory alloys possess slightly varied ranges of transformation temperatures—temperatures that trigger their memory to restore them to their original state—rendering different alloys suitable for diverse construction purposes.

**Applications in Construction**

**1. Bridge Reinforcement**

In their initial application, shape-memory alloys were introduced as reinforcement for a concrete structure within a highway bridge located in Michigan. This particular bridge had experienced the accumulation of substantial cracks over a period, leading to concerns about its overall structural stability. In an effort to enhance its strength and durability, engineers incorporated rods made of iron-manganese-silicon-chromium shape-memory alloy into the bridge's girder. Following this successful implementation, the utilization of shape-memory alloys has extended to other bridge constructions, aiming to augment their resilience and capacity to withstand damage owing to their inherent elasticity.

**2. Restoration of Heritage Structures**

Numerous architectural heritage sites have necessitated restoration and reinforcement due to years of wear and deterioration. The Istech initiative engineered a specialized metallic alloy apparatus for this precise purpose. They designed pre-tensioned wires using nickel-titanium shape-memory alloy, which exhibited superelasticity in both directions. These innovative devices have been strategically integrated into structures using varying techniques—depending on whether the goal was to forestall deformations or potential building collapses. Subsequent to their creation, these shape-memory alloy devices have found practical application in significant edifices, exemplified by the bell tower of San Giorgio church in Trignano, Italy, which endured earthquake-induced damage.

**3. Enhancing Building Seismic Performance**

Shape memory alloys have also been harnessed to craft devices akin to those delineated earlier, with the purpose of safeguarding structures against seismic activity. While this technology currently cannot preempt the emergence of cracks during an earthquake, it effectively curbs excessive deformation and potential collapse during subsequent aftershocks.



**Fig. 1 Working Mechanism of SMAs**

**Advantage of SMAs**

* SMAs exhibit high strength
* SMAs possess the property of Super elasticity
* SMAs have good fatigue and wear resistance
* SMAs are easy to fabricate
* SMAs have a high power/weight ratio
* SMAs are light in weight
* SMAs have an amazing bio compatibility

**Limitations of SMAs**

* Initial investment is high
* Sensitive fabrication
* Residual stress

**PIEZOELECTRIC MATERIALS**

These materials generate electric voltage in response to applied mechanical stress and vice versa. In civil engineering, they can be embedded in structures to harvest energy from vibrations, monitor structural health by detecting changes in strain, or actively dampen vibrations to mitigate seismic impacts.

Piezoelectric materials represent a distinctive class of substances that can generate an electric voltage when subjected to mechanical stress or pressure, and conversely, they can change their shape when an electric field is applied. This phenomenon arises from the arrangement of their internal crystal structure, which results in the separation of positive and negative charges within the material.

By using piezoelectric materials that create electrical energy under mechanical stress or mechanical stress under electrical energy, it will be possible to obtain energy at the same time by controlling these vibrations affecting the structure. In this way, the building will produce its own energy and reduce the energy obtained by consuming natural resources in the world. Piezoelectric materials can be used as the energy generators in buildings as an operating energy for water heating and ventilation. In addition to the energy problem, vibrations around the world from the energy released as a result of the movement of underground faults, in other words, earthquakes, cause heavy damage to the structures.

The most well-known piezoceramic materials are the lead zirconate titanate (Pb–Zr–Ti) and the barium titanate (BaTiO3).

**Applications of Piezoelectric Materials**

1. **Vibration Energy Harvesting:** Piezoelectric materials can be integrated into structures to capture ambient vibrations caused by sources such as foot traffic, vehicle movement, or wind. This harvested energy can then be used to power low-energy devices or sensors without the need for external power sources.
2. **Structural Health Monitoring:** By embedding piezoelectric sensors within buildings, bridges, or other infrastructure, engineers can monitor the structural health and integrity of these systems. Changes in strain, stress, or deformation can be converted into electrical signals for real-time analysis.
3. **Smart Materials and Adaptive Structures**: Incorporating piezoelectric materials into building components allows for the creation of adaptive structures. These structures can adjust their shape, stiffness, or damping properties in response to external forces, improving their performance during dynamic events like earthquakes or strong winds.
4. **Vibration Damping:** Piezoelectric actuators can actively control vibrations in structures by converting electrical energy into mechanical vibrations. This is particularly useful in reducing unwanted vibrations and enhancing comfort in buildings and bridges.
5. **Energy-Efficient Sensing:** Piezoelectric sensors can detect changes in pressure, stress, and strain, making them valuable for applications such as load monitoring, impact detection, and even as part of seismic sensing systems.
6. **Energy Generation from Foot Traffic:** In high-foot-traffic areas, piezoelectric materials can be integrated into floors or walkways to generate electricity from the mechanical energy of people walking, potentially contributing to local power needs.
7. **Structural Vibration Control:** Piezoelectric devices can be used to actively dampen vibrations in structures, mitigating the impact of external forces like earthquakes or strong winds.

While piezoelectric materials offer numerous advantages, including their energy efficiency and adaptability, challenges such as material durability, efficient energy conversion, and integration into existing structures remain areas of active research and development within the field of civil engineering.

**Advantages**

* Piezoelectric materials are adaptable to diverse temperature conditions.
* Their minimal carbon footprint positions them as an excellent alternative to fossil fuels.
* Their inherent characteristics render them highly effective energy harvesters.
* Unutilized energy existing as vibrations can be harnessed to generate eco-friendly power.
* These materials can be recycled, contributing to sustainability.

**Limitations**

* Devices reliant on piezoelectric principles are susceptible to capturing extraneous vibrations during operation.
* Resistance and durability issues impose constraints on the use of these devices for energy extraction from pavements and roads.
* The disparity in stiffness between piezoelectric materials and pavement substances can be problematic.
* A paucity of comprehensive understanding about these devices, along with limited research conducted to date, hinders the realization of their full potential.

**SELF-HEALING CONCRETE**

Incorporating materials like encapsulated polymers, bacteria, or other compounds into concrete can allow it to heal cracks autonomously. When cracks form, these materials are triggered to react and seal the cracks, enhancing the longevity and durability of concrete structures.

Self-healing concrete is defined as the ability of concrete to repair its cracks autogenously or autonomously, while cracks in concrete are a common phenomenon due to their relatively low tensile strength, it is also called self-repairing concrete.

It is an artificial or synthetically made material with an inherent ability to repair damage on its own, without any external diagnosis or human intervention.

Self-healing concrete is often known as “Bio Concrete” or “Bacterial Concrete”, it is specifically designed to increase the durability of concrete structure by self-healing action of that concrete.

This concrete was invented by a group of microbiology researchers under the Henk Jonkers, while in most conventional concrete mixtures, 20–30% of cement is left un-hydrated.

If cracking of concrete occurs unreacted cement, grains may become exposed with moisture entering the crack and the hydration process can resume and the hydration products can fill and fix the crack.

**Applications of Self-healing concrete:**

1. It can be actively used in the case of roads to reduce traffic jams.
2. Also used by the oil and gas industries, preventing small cracks from spreading.
3. It can be used to strengthen both existing and new types of structural building.
4. It is effective in areas where buildings undergo freezing and thawing.
5. This can prove to be economical in the case of irrigation works, dams that are directly in contact with water.
6. This concrete can be used for sectors such as tunnel-linings, structural basement walls, highways, bridges, concrete floors, and marine structures.
7. It is a new technology that can give way to sustainable roads.
8. In high strength buildings with more bearing capacity.

**Advantages of Self-healing concrete:**

* This concrete has comparatively much lower permeability, greater durability, and stress carrying capacity than conventional concrete.
* It can be applied to existing buildings in the form of spray which can reduce the overall repair and maintenance costs of the buildings.
* This is an environmentally friendly technique because the carbon dioxide produced is prevented due to the low use of concrete.
* SHC is a more effective shock absorber that protects during earthquakes because it has a polymer membrane on its surface.
* It can operate at internal levels which means that the smallest cracks can be reached.
* Un-hydrated cement that does not contribute to strong participation can be used.
* These [types of concrete](https://constructionor.com/types-of-concrete/)help to fill the crack.
* Improvement in the compressive strength of concrete.
* Better resistance to freeze-melting attack reduction.
* Also, helps to reduce maintenance and repair.
* Self-healing concrete can get self-repair without any external treatment.
* Reduce corrosion of steel as crack self-repair which is a major reason starting corrosion.
* In self-healing concrete, bacteria used in this concrete-like Bacillus bacteria are harmless to human life and hence it can be used effectively.

**Disadvantages of self-healing concrete:**

* The cost of self-healing concrete is double that of conventional concrete.
* The growth of any bacteria is not good in any atmosphere media.
* Calcite precipitation investigations are expensive.
* Skilled labor is required.
* In this reaction mechanism, the 2 ammonium ions are generated simultaneously for every carbonate ion, which can lead to extreme environmental nitrogen load.
* The matrix of concrete changes and reduces the amount of mixing thus reducing the strength of the concrete.
* Power boost is a fairly slow process.

**SHAPE-SHIFTING POLYMERS**

Polymeric materials with the ability to alter their shape in response to external factors like changes in temperature or moisture hold promising potential in adaptive architecture. Applications in this field include self-regulating ventilation systems or roofs capable of adjusting their configuration to optimize solar exposure.

Shape-memory polymers (SMPs) represent a category of intelligent polymers that can transition from a deformed state (temporary shape) back to their original (permanent) shape when subjected to an external stimulus, typically a temperature alteration.

Shapeshifting metals exhibit the capacity to undergo stress-induced temporary shape changes and subsequently "remember" and revert to their original form. In architectural contexts, their deployment, for instance, in constructing bridges, could mitigate damage caused by events like tropical storms or earthquakes. The incorporation of this type of metal in the construction industry remains in the developmental phase, with researchers exploring its applications in civil infrastructure.

**Properties of Shape-Shifting Polymers**

* Higher yield strength in comparison to plastic or aluminum.
* Significant recoverable plastic strain.
* Elevated manufacturing costs.
* Lightweight composition.

**Applications**

* Bridges.
* Earthquake-resistant buildings.
* Intelligent Reinforced Concrete (IRC).
* Shape-memory coupling for piping.
* Addressing conditions like Essential Tremor.

**Limitations**

* Susceptibility to rust, leading to structural weakening and shortened building lifespans.
* Elevated costs compared to alternative materials like concrete.
* Environmental concerns due to pollution from metal ore extraction and depletion of finite Earth resources.

**SMART SENSORS**

Advanced sensors embedded in structures can continuously monitor factors like strain, stress, temperature, and corrosion. This real-time data helps engineers assess structural health and detect potential issues before they become critical.

So, what is the difference between a regular sensor and a smart sensor? The main difference is that smart sensors typically contain microprocessors that perform basic data processing, such as edge computing that is then shared with a central data repository located for analysis.

These devices can be used to monitor and control mechanisms in a wide variety of applications and environments including smart grids, road conditions, bridge integrity, rainfall monitoring, public engagement and much more.

Smart sensors are small, wireless devices that can be incorporated into building materials, equipment, or even workers’ clothing. They are intended to collect and send vital data pertaining to various areas of construction projects. This information can include temperature, humidity, pressure, vibration, strain, noise levels, and much more.

The fundamental purpose of utilizing smart sensor in construction is to allow for real-time monitoring and analysis of crucial data. This enables project managers, contractors, and other stakeholders to make educated decisions, spot problems early, and adopt corrective actions quickly. Smart sensors increase safety, optimize resource allocation, and boost overall project efficiency by giving accurate and up-to-date information.

Smart sensor integration in construction offers the ability to improve procedures, reduce hazards, and boost productivity. However, it is critical to solve issues such as data management, security, and sensor system compatibility. Smart sensors are projected to play a significant role in determining the future of the construction industry, allowing smarter, safer, and more sustainable building processes as technology advances.

**Types of Smart Sensors in Construction**

**1. Structural Monitoring Sensors**: These are essential for detecting changes in the physical conditions of structures, from bridges to skyscrapers. They monitor vibrations, deformations, and stresses, providing vital data for predictive maintenance. For example, piezoelectric sensors can measure dynamic pressure changes, while fiber optic sensors offer accurate strain measurements.

**2. Environmental Sensors:** These sensors provide real-time data on environmental conditions at the construction site. They track variables like temperature, humidity, wind speed, and air quality. Environmental sensors ensure that the construction activities are not adversely impacting the environment and provide a safer workspace. For instance, particulate matter sensors can detect airborne dust and pollutants.

**3. Safety Sensors:** These are designed to prevent accidents and injuries on construction sites. Examples include wearable sensors, which can monitor workers’ health and alert if there’s a risk of heatstroke or fatigue. Proximity sensors alert workers when they are near dangerous equipment or zones, while gas sensors detect harmful gases, preventing potential hazards.

**4. Geotechnical Sensors:** These help in monitoring the stability of soil and rock masses, essential for tunneling, excavation, and construction of foundations. Inclinometers and extensometers are often used in this category to track ground movements.

**5. IoT-based Sensors:** These are smart sensors connected via the Internet of Things. They can collate and transmit data to a centralized system, facilitating real-time monitoring and decision-making. An example could be an RFID (Radio Frequency Identification) sensor used for tracking equipment and materials.

**6. Drones and LIDAR Sensors:** These are used for surveying and mapping construction sites. Drones equipped with LIDAR sensors provide high-resolution 3D models of the construction area, aiding in precise planning and execution.

**Applications of Smart Sensors in Construction**

Smart sensors are the technological linchpin in modern construction, offering a range of applications that enhance safety, efficiency, and productivity.

**1. Monitoring Structural Conditions:** Sensors embedded within construction materials can detect changes in pressure, temperature, or vibrations, providing real-time data on the health of structures. This facilitates early identification of potential problems, reducing the risk of catastrophic failure.

**2. Anomaly Detection:** Beyond routine monitoring, smart sensors can identify anomalies that might indicate more serious structural issues. For example, changes in magnetic fields or electrical resistance could suggest hidden damage that requires immediate attention.

**3. Resource Usage Monitoring:** Smart sensors can track the usage of resources like water, electricity, or gas in real-time, providing actionable insights into consumption patterns and potential wastage.

**4. Energy Efficiency:** smart sensors, particularly in HVAC systems, can optimize the use of energy by adjusting temperature and lighting based on occupancy and ambient conditions. This not only reduces energy waste but also contributes to a more sustainable construction industry.

**5. Safety Management:** Construction sites often pose various hazards. Smart sensors can continuously monitor these potential risks, such as equipment health or gas leaks, and provide alerts to prevent accidents.

**6. Accident Prevention:** Smart sensors also play a key role in preventing accidents. They can monitor worker movements to ensure they remain in safe zones, reducing the likelihood of mishaps.

**7. Worker Health Monitoring:** Wearable sensors can track worker health parameters such as heart rate, body temperature, or fatigue levels, providing real-time feedback to supervisors and promoting worker safety.

**8. Environmental Monitoring:** Smart sensors can measure environmental conditions such as air quality, noise levels, and radiation exposure at construction sites, ensuring adherence to regulatory standards and worker safety.

**MAGNETORHEOLOGICAL (MR) FLUIDS**

These fluids change viscosity in the presence of a magnetic field. In civil engineering, MR fluids can be used to create smart dampers that adjust their properties in real-time to absorb or dissipate energy, improving the performance of structures during seismic events.

A magnetorheological (MR) fluid is a fluid that has good magnetic properties. MR fluid responds to the magnetic field and changes its properties when a magnetic field is presented. The areas of application for MR fluids are MR dampers, brakes, clutches and MR valves.

**PHOTOCHROMIC AND THERMOCHROMIC MATERIALS**

These materials change color in response to light or temperature changes, respectively. In architectural applications, they can be used for adaptive shading systems that automatically adjust to changing lighting conditions.

**CARBON FIBER REINFORCED POLYMERS (CFRPS)**

Carbon Fiber Reinforced Polymers (CFRPs) are composite materials valued for their high strength-to-weight ratio. In civil engineering, they are utilized for retrofitting and reinforcing existing structures, enhancing their load-bearing capacity and longevity.

Carbon fiber reinforced polymers (CFRPs) encompass a composite composition comprising carbon fibers and polymers. The carbon fibers provide strength and rigidity, while the polymer acts as a cohesive matrix, securing and binding the fibers together. CFRPs are manufactured in various forms such as strips, bars, and sheets using techniques like filament winding, pultrusion, and hand lay-up processes.

Noteworthy properties of CFRP materials include good rigidity, high strength, low density, corrosion resistance, vibration dampening, high ultimate strain, notable fatigue resistance, and low thermal conductivity. They possess insulating properties for electricity and are non-magnetic.

CFRPs offer solutions to multiple infrastructure challenges, such as corrosion control and structural reinforcement. By incorporating CFRP reinforcing bars into new concrete, potential corrosion issues can be mitigated while significantly augmenting structural robustness.

Leveraging carbon fiber reinforced polymers can substantially extend the lifespan of structures, reducing maintenance demands. Carbon fibers also serve as reinforcement for lightweight, high-strength structures.

**Properties of CFRP:**

* Alkali-resistant.
* Corrosion-resistant, facilitating corrosion control and reinforced concrete structure rehabilitation.
* Low thermal conductivity.
* High strength-to-weight ratio, reducing the need for heavy construction equipment.
* Short curing time, leading to quicker application, reduced project duration, and less downtime.
* High ultimate strain.
* High fatigue resistance, minimizing maintenance requirements.
* Non-conductive of electricity and non-magnetic.
* Lightweight, enabling easy transportation of prefabricated CFRP components and encouraging prefabricated construction.

**Applications of CFRP in Concrete Structures:**

1. **CFRP Strips:** Used in various techniques like externally bonded CFRP sheets and near-surface mounted FRP for strengthening concrete structures. CFRP strips offer advantages such as ease of handling due to their high strength-to-weight ratio.
2. **CFRP Wraps:** Employed for masonry column rehabilitation and reinforcement, corrosion control of reinforced concrete columns, and construction of earthquake-resistant structures.
3. **CFRP Laminates:** Used to strengthen structural members like beams and girders. They contribute to increased ultimate flexural moment capacity.
4. **CFRP Bars:** Utilized in constructing new buildings and reinforcing existing structures through techniques like near-surface mounted CFRP reinforcement.

CFRPs stand as versatile materials contributing to the durability and resilience of civil engineering projects.

**Advantages**

* **High tensile strength:** Carbon fibers are more flexible than steel or concrete, meaning CFRP can withstand more pressure without cracking.
* **Fatigue resistance:** The material resists degradation, so structures that use it require less maintenance overall.
* **Strength against the elements:** CFRP can withstand severe environmental conditions, from humidity and heavy rainfall to chemical exposure.
* **Light weight:** While CFRP is costlier than some other building materials, it’s light in weight. As a result, it costs less to transport and results in lower labor costs because installation requires fewer workers.

**Limitations**

* Carbon fibre products are expensive compared to other structural building materials used for the same jobs. Though, while products like aluminium and steel are cheaper initially, they require more manpower due to the weight. We always recommend booking a cost analysis before deciding – that way you can notice the price difference and whether it’s worth it for you.
* It conducts heat and electricity, so it may not be the best choice for your project if your building or structure works with either of these elements. We always recommend booking a feasibility analysis to see whether carbon fibre-reinforced polymer is the right option, or whether there’s a suitable alternative.