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How to Make Concrete More Ductile - A State Of Art

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Abstract— **The earthquakes that occur on Planet Earth each year may be around 5,00,000 but people will "feel" about 1,00,000 of them and about 100 will cause damage. Although most earthquakes are moderate in size and destructive potential, a severe earthquake occasionally strikes a community that is not adequately prepared and thousands of lives and billions of dollars in economic investment are lost. Within the past 200 years, major destructive earthquakes also occurred in India, Japan, Nepal and other countries. Within the past 50 years, smaller but damaging earthquakes occurred several times in both India and Japan. Overall, more than 20 countries have a moderate or high risk of experiencing damaging earthquakes. Earthquakes are truly a national problem. One of the key ways a community protects itself from potential earthquake disasters is by adopting and enforcing a building code with appropriate seismic design and construction standards. Hence the basic approach of earthquake resistant design should be based on lateral strength as well as deformability and ductility capacity of the structure with limited but no collapse.**

Index Terms— **Ductility of concrete, Bendable concrete Metakaolin, PVA fibers and Nano Materials.**

I. INTRODUCTION

The loss of life from the recent earthquakes in Nepal is approached the scale of the earthquake that devastated Japan in 2011, where more than 20,000 perished. Experience in past earthquakes has demonstrated that many common buildings and typical methods of construction lack basic resistance to earthquake forces [1]. In most cases this resistance can be achieved by following simple, inexpensive principles of good building construction practice. Desirable properties of earthquake-resistant design include ductility and deformability. Ductility and deformability are interrelated concepts signifying the ability of a structure to sustain large deformations without collapse [2]. One of the key ways a community protects itself from potential earthquake disasters is by adopting and enforcing a building code with appropriate seismic design and construction standards.

The collapse of RCC building is preventable if Failure is ductile rather than brittle-ductility with large energy dissipation capacity. The member should be designed for the case where Flexure failure should precede shear failure. The design of Beams should be such that they fail before columns and the connections should be stronger than the members [3]. The structures are to be designed to have sufficient strength and ductility for safety against earthquake forces. Both strength and ductility are important for seismic safety [4]. The current codal practice of design of RC buildings is based on a linear analysis and Limit State Design philosophy. The effect of ductility is considered in the form of a "response Reduction Factor", which is used to reduce the earthquake forces for design.

IS 13920:1993(Reaffirmed 2003) recommends the following provisions to improve the Ductility of Reinforced concrete structures subjected to seismic forces

(i) Minimum length of 135^0 hooks ≥ 75 mm.

(ii) Minimum tension steel ratio ≥ $0.24\sqrt{(f_{ck}/f_y)}$

(iii) Longitudinal bars shall be spliced only if hoops are provided over the entire splice length at a spacing not exceeding 150 mm.

(iv) Top and bottom bars of the beam shall be provided with Anchorage length beyond the column face = $L_d + 10\ d_b$.

No emphasis has been given on improving the ductility of concrete material as a whole, but by providing extra reinforcement at critical locations which is a passive way of approaching the problem.

II. DESIGNS FOR DUCTILITY

As mentioned earlier, the Response Reduction Factor, used in the design of structures depends on ductility of the structure. The ductility of structures, in turn, depends on the ductility of individual components and structural configuration, including relative strength of different components and redundancy [5].

The RC members are to be designed for three actions: (i) Axial Force, (ii) Shear Force, and (iii) Bending Moment. Beams are generally monolithic with slabs and these are not designed for axial load. On the other hand, the columns are to be designed for an interaction of axial load and bending moment. The design for Shear is independent.

Concrete is known to be brittle material. Typical to brittle materials, it has much lower strength in tension, than in compression. The behaviour of concrete can be greatly enhanced by confining it [6]. The ductility of concrete can be significantly improved by proper detailing of the reinforcement. This Chapter deals with important aspects of the design and detailing of RC buildings. Hence in the case of reinforced concrete members subjected to inelastic deformation, not only strength but also ductility plays vital role in the design [7]. A ductile material is the one that can undergo large strains while resisting loads. Graph shown in Fig 1 gives comparison between brittle and ductile material.

The Advantages of providing ductility to a structure are listed below:

1. A ductile RC structure may take care of overloading, load reversals, impact and secondary stresses due to differential settlements of foundations.
2. A ductile reinforced concrete structure gives the occupants sufficient time to vacate the structure by showing large deformations before its final collapse.
3. Ductility property of a material absorbs shocks induced by dynamic loads, thereby reducing the risk of failure during earthquake.

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Thus ductility of a structure is in fact one of the most important factor affecting its seismic performance. The prevailing Indian code IS 13920: 2003[8] ensures the overall ductility of the structure by providing extra reinforcement at critical locations of the structure like junctions. It did not give any emphasis on increasing the ductility of the concrete used in construction. Concrete is a brittle material and its tensile strength is negligible. Improving the properties of concrete like ductility, tensile strength and energy dissipation capacity by introducing different types of admixtures/materials will be a revolutionary approach in the field of construction. Lot of research is going on in this area and few different concretes have emerged.

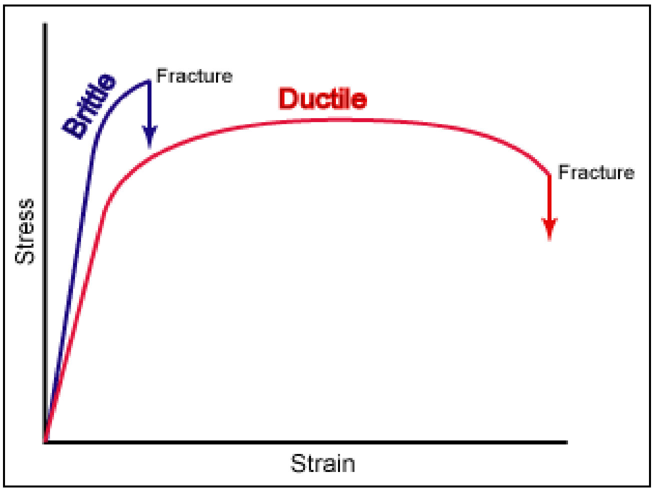


Fig (1) Brittle and ductile behaviour of concrete

They latest researches ongoing in the area of enhancing the ductility and toughness of concrete for earthquake resistant structures are as mentioned below:

1. Strain-hardening cementitious composites (SHCC)/Bendable concrete
2. Ultra-High performance Ductile Concrete
3. High Strength Ductile Concrete incorporating Metakaolin and PVA fibers.
4. Nano Materials.

III. LITERATURE REVIEW

In recent years, the increasing attention to the need for structural resiliency and environmental sustainability has shed new light on the limitations of concrete material. There are plenty of visual examples of fracture failure of reinforced concrete members during major earthquakes, for example. It is also known that the durability of concrete structures is often compromised by the presence of cracks while exposed to an aggressive environment. The high carbon and energy footprints of civil infrastructure are closely linked to the need for repeated repairs during its service life.

The most important concrete property is compressive strength. Tensile forces are expected to be carried by prestressing or reinforcing steel (Passive Combination). These fundamental structural design concepts of putting concrete in compression and steel in tension have largely worked very well. A ductile concrete can result in high structural load capacity, even though high structural strength is more commonly associated with high material strength [9, 10]. For structural members whose capacity is limited by brittle fracture failure of concrete, the governing parameter is tensile ductility, not the compressive strength.

IV. STRAIN-HARDENING CEMENTITIOUS COMPOSITES (SHCC)/ BENDABLE CONCRETE:

S. Billington et.al [5]: conducted a comparative test of a shear panel using a normal concrete of 7,250 psi compressive strength and a ductile concrete of 5,950 psi compressive strength. The ductile concrete panel yielded a higher structural shear capacity of 12,590 lbf compared to 8,540 lbf for the normal concrete panel. This illustrates that structural capacity does not always correlate with material compressive strength. Apart from enhancing load capacity, ductility of concrete also embeds damage tolerance, and therefore resiliency, into structures. While concrete structural durability is often associated with concrete impermeability, there is evidence that a densely packed concrete does not always translate into structural durability.

P.K. Mehta et.al [5]: examined the durability of concrete bridge decks and concluded that those built with high strength, densely packed concrete have, in recent years, demonstrated a lower service life than their predecessors using lower strength concrete. The underlying cause of the discrepancy in durability expectations is that the lower permeability concrete is measured in the laboratory without load application, whereas the field permeability of concrete structures under load is dominated by the presence of cracks. Hence, material durability (impermeability) does not always translate into structural durability. Instead, a ductile concrete can suppress cracking with wide crack width and lend itself to supporting structural durability. A ductile concrete, with substantially higher tensile ductility compared to normal concrete, can contribute to higher structural resiliency and environmental sustainability, the latter by virtue of the need for less frequent repairs.

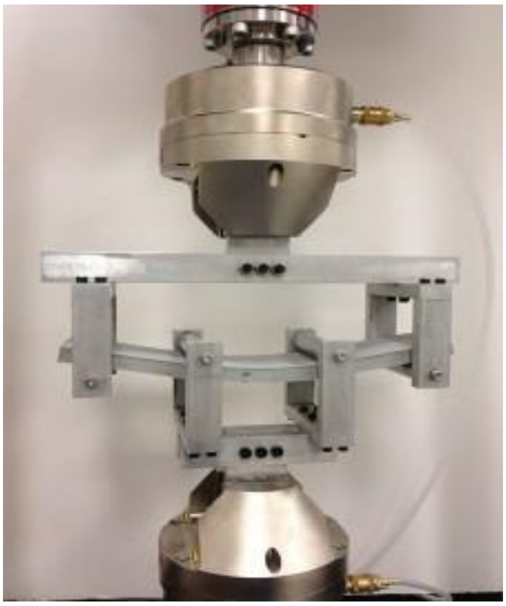


Fig. 2: Ductile SHCC under bending.

Victor Li, [5]: The technology to making concrete ductile, with tensile strain capacity several orders of magnitude higher than normal concrete, has been realized in recent years. This class of concrete, often known as strain-hardening cementitious composites (SHCC), exhibits a tensile stress-strain curve with a shape that resembles that of a ductile metal, while maintaining a compressive strength of that of a normal to high strength concrete. While still expensive, the material has found its way into full-scale structural applications in several countries and especially in Japan. In the popular press, SHCC has often been called “Bendable Concrete” due to its ability to undergo large flexural deformation even without steel reinforcement (Fig.2).

Figure 3 illustrates the change in building design with the introduction of this new SHCC technology, utilized in high-rise construction project in Japan. In the design without SHCC (Figure 3a), the building self-centers under seismic loading by means of two pairs of super-frames that bracket the whole building in two perpendicular directions. Each super-frame is constructed of two huge columns that rise from the building foundation to the top of the building, and connected through dampers at the ends of an enormous sky beam. The 9-foot- deep beam is difficult to hoist to the top of the building, requiring fabrication at the building top. In the SHCC design (Figure 3b), the super-frames were eliminated and replaced with four SHCC precast coupling beams to connect the core walls on each floor. The damage tolerant SHCC coupling beams are expected to undergo large shear deformation in a ductile mode with high energy-absorption capability.

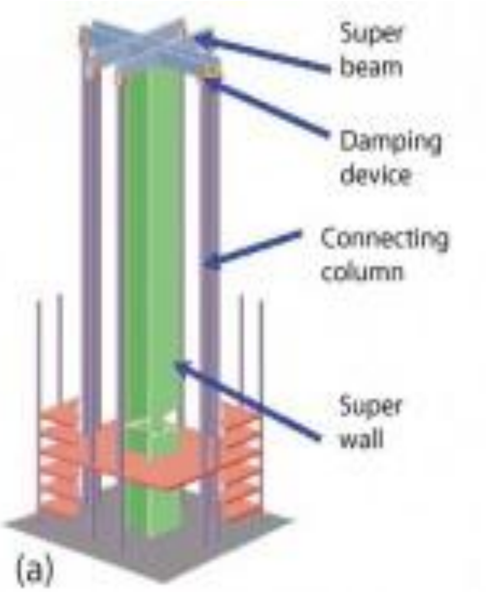
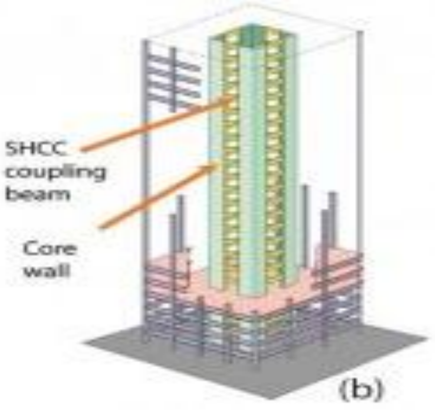


Fig. 3: (a) Previous design with super-frame

The primary feature of SHCC is its ability to meet tensile deformation and durability demands. Ductile concrete can serve as a new material technology that contributes to enhancing civil infrastructure resiliency and sustainability. Although current application of the material remains limited, the advantages of ductile concrete will likely broaden its adoption in coming years when a supply chain of this new class of concrete is established globally.



3 (b) New design with SHCC coupling beams.

V. ULTRA-HIGH PERFORMANCE DUCTILE CONCRETE

The innovation of Ductal ultra-high performance, fiber reinforced concrete (“UHPFRC”) is a revolutionary material that offers superior strength, durability, ductility and aesthetic design flexibility [9]. It is significantly stronger than conventional concrete, with compressive strengths up to 30,000 psi and flexural strengths up to 6,000 psi. It is blended with metallic or PVA fibers, depending on strength and rheology requirements, exposure to corrosive agents, desired aesthetics and other factors. Available in a range of colors, it is extremely moldable and replicates form materials with great precision. By utilizing Ductal’s combination of superior properties, designers can create thinner sections and longer spans that are lighter, more graceful and innovative in geometry and form, while providing improved durability and impermeability against corrosion, abrasion and impact.

The ductile behaviour is a first for a concrete material; with the capacity to deform and support flexural and tensile loads, even after initial cracking [9, 10]. Its superior strength allows for solutions with smaller elements, without the use of passive reinforcing steel and, in most applications, without prestressed or post-tensioned reinforcement.

There is almost no carbonation or penetration of chlorides and sulphides. The material has improved freeze-thaw and abrasion resistance due to an optimized gradation of fine powders, selected for relative grain size (maximum 600 microns) and chemical reactivity. Ductal is approximately 5% denser than conventional concrete. This “denseness”, along with small, similar sized, non-connected pores throughout the cementitious matrix, attributes to its imperviousness and durability against adverse conditions and aggressive agents. The material has almost no shrinkage or creep, making it suitable for prestressed applications. The material is highly moldable due to the fine grain constituents, self-consolidating properties, and absence of reinforcing steel, thereby allowing designers to develop new, lighter complex shapes with enhanced surface aspects.

Advantages may include: reduced global construction costs, formworks, labor and maintenance, which relates to improved site construction safety, speed of construction and, extended usage life.

What it changed or replaced: Many economies gained with Ductal are a result of engineering new solutions for old problems. With its combined, superior properties and related benefits, Ductal replaces conventional building materials (including steel) with attractive, durable and cost-competitive solutions for a variety of innovative applications. The proven successes to date demonstrate its unique capabilities and leads to new possibilities for civil engineering, structural reinforcement and contemporary architectural works.

VI. HIGH STRENGTH DUCTILE CONCRETE INCORPORATING METAKAOLIN AND PVA FIBERS.

The mechanical properties of high-strength ductile concrete (HSDC) have been investigated using Metakaolin (MK) as the cement replacing material and PVA fibers [11]. Large industrial and economic growth caused a massive increase in cement and steel usage which are main building construction materials.

The cement and steel producing industries contribute about 5% to 7% of global CO_2 emissions and today concrete industry is the largest consumer of natural resources such as water, sand, gravel and crushed rock. Therefore for sustainable and environmentally viable development, large production of cement and steel is undesirable and gradual reduction in the use of cement and steel is needed. Several researchers investigated and supplementary materials for cement and steel, but cement and steel cannot be completely replaced with any other supplementary material. Cement can only be partially supplemented by mineral admixtures such as fly ash, silica fume, ground granulated blast furnace slag, rice husk ash and Metakaolin (MK) and use of steel can be partially reduced by introducing ductility in concrete [11].

MK possesses substantial content of silica and alumina in comparison with cement and other mineral admixtures showing the capability to produce both strengthening gel, that is calcium silicate hydrate (CSH) and calcium aluminates hydrate (CAH) by reacting with the primary hydrate of cement. The early strength gained is higher with the addition of MK in comparison with fly ash and silica fume. Also increase in the tensile and bending strength of concrete and mortar with 10 to 15 % MK if 32% and 38% respectively, and it is better than silica fume. Low tensile strength of concrete is due to propagation of single internal crack. If the crack restrained locally by extending into another matrix adjacent to it, the initiation of crack is retarded and higher tensile strength of concrete is achieved. This can be achieved by adding small length fibers to concrete. In addition to increasing the tensile strength, addition of fibers enhances fatigue resistance, energy absorption, toughness, ductility, and durability.

Polyvinyl alcohol (PVA), an organic fiber, was explored 50 years age by Japanese and has been used in cement applications since the 1980s. PVA fibers have tensile strength and young's modulus higher than other organic fibers. The most important characteristics of PVA fiber is the strong bond with cement matrix, higher modulus of elasticity, and bond strength of PVA. These add more flexibility and tensile strength in concrete. The basic focus of the current study is to use MK and PVA fibers together in order to lessen the use of cement and steel without compromising the performance.

In HSDC, the target is to reduce the cement content and induce ductility without compromising the performance. The results show that, the compressive strength of concrete wit 5% and 10 % MK has increased about 5% and 16.5 % at age of 28 days as compared to control.MK together with PVA fibers of aspect ratio 45, 60, and 90 up to 2% fibers volume fractions, has been found comparable with control.

Similar to compressive strength, splitting tensile strength increases with age and with increase in volume fraction of fibers from 1 to 2 %. Inclusion of 5 to 10 % MK caused 16.5 % and 24 % increase in splitting tensile strength at age of 28 days as compared to control.5% Mk together with PVA fibers has higher splitting tensile strength with PVA fibers having aspect ratio 45, 60, and 90 with 2% volume fraction.

A. NANO MATERIALS

Nano Technology was introduced by Nobel laureate Richard P. Feynman [12] during his famous 1959 lecture " There's Plenty of Room at the Bottom," there have been many revolutionary development in Physics, Chemistry, and Biology that have demonstrated Feynman's ideas of manipulating matter at an extremely small scale, the level of molecules and atoms, i.e., the nanoscale.

Definition: Nano Technology is defined as the understanding, control, and restructuring of matter on the order of nanometers to create materials with fundamental new properties and functions.

Abstract: The role of Nano technology in the conceiving of innovative infrastructure systems has the potential to revolutionize the Civil Engineering practice and widen the vision of civil engineering. Following this the analysis were carried out in ductile structural composites along with its enhanced properties, low maintenance coatings, better properties of cementitious materials, reducing the thermal transfer rate of fire retardants and insulation, various Nano sensors, smart materials, intelligent structure technology etc., to execute there, the gap between the nanotechnology and construction materials research needs to be bridged.

Introduction: Nanotechnology is the use of very small particles of materials either by themselves or by their manipulation to create new large scale materials. Nanotechnology is not a new science and it is not a new technology, it is rather an extension of science and technologies.

At 'nano scale' the world is different from 'macro scale' e.g,. the gravity becomes unimportant, electrostatic forces take over and quantum effects emerge [12]. As particles become nano sized, the proportion of atoms on the surface increases relative to those inside leads to 'nano-effects'. Nano-engineering encompasses the techniques of manipulation of the structure at the nanometer scale to develop a new generation of tailored, multifunctional, cementitious composites with superior mechanical performance and durability potentially having a range of novel properties such as: low electrical resistivity, self-sensing capabilities, self-cleaning, self-healing, high ductility, and self-control of cracks.

Nanotechnology encompasses two main approaches: (i) the "top-down" approach, in which larger structures are reduced in size to the nanoscale while maintaining their original properties without atomic level control. (ii) the "bottom-up" approach, also called "molecular nanotechnology" or "molecular manufacturing," introduced by Drexler et al., in which materials are engineered from atoms or molecular components through a process of assembly or self-assembly[13]. While most contemporary technologies rely on the "top-down" approach, molecular nanotechnology holds great promise for breakthroughs in materials and manufacturing, electronics, medicine and healthcare, energy, biotechnology, information technology, and national security.

Nanosized particles have a high surface area to volume ratio, providing the potential for tremendous chemical reactivity. Much of the work to date with nanoparticles has been with nano-silica (nano-SiO_2) and nano-titanium oxide (nano-TiO_2). There are a few studies on incorporating nano-iron (nano-Fe_2O_3), nano-alumina (nano-Al_2O_3) and nanoclay particles.Nano-SiO_2 has been found to improve concrete workability, strength, resistance to water penetration. Even addition of small amounts (0.25%) of nano-SiO_2 was observed to increase the 28 day compressive strength by 10% and flexure strength by 25 %.

Nano-TiO_2 has proven very effectively for the self-cleaning of concrete and provides the additional benefit of helping to clean the environment. “Self-cleaning” and “de-polluting” concrete products are already being produced by several companies for use in the facades of building and in paving materials for roads have been used in Europe and Japan. Nano- Fe_2O_3 has been found to provide concrete with self-sensing capabilities as well as to improve its compressive and flexural strength. Nano- Al_2O_3 has been shown to significantly increase the modulus of elasticity (up to 143% at a dosage of 5%) but have limited effects on the compressive strength, and no novel properties have been reported.

Recently, the concept of a nano binder has been proposed. This concept involves mechano-chemical activation that is obtained by inter-grinding cement with dry mineral additives in a ball mill. Mechano-chemical modification of cement with high volumes of blast furnace slag has been shown to increase the compressive strength by up to 62 %. Nanoclay particles have shown promise in enhancing the mechanical performance, the resistance to chloride penetration, and the self-compacting properties of concrete and in reducing permeability and shrinkage. Chemical binding of PVA (Polyvinyl alcohol) to exfoliated clay particles recently has been proposed to create linked clay particle chains that, when incorporated in cement, were shown to improve the post-failure properties of the materials.

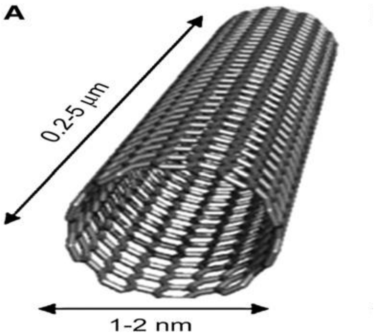


Fig.4(a) single-walled carbon nanotube (SWCNT)

Modification of the structure of C-S-H at the nanoscale to create hybrid, organic, cementitious nanocomposites lately has received attention due to the interest in more sustainable concrete structure. Nanoreinforcements: carbon nanotubes/nanofibers (CNTs/CNFs) are potential materials for use as nanoreinforcements in cement-based materials. Carbon nanotubes are cylindrical in shape with diameter in nanometers and length can be in several millimeters as shown in figures 4 (a) & 4(b). When compared to steel, the Young’s modulus of CNTs is 5 times, strength is 8 times while density is 1/6th times. CNTs/CNFs exhibit extraordinary strength with moduli of elasticity on the order of Tera Pascal (TPa) and tensile strength in the range of GPa, and they have unique electronic and chemical properties. CNTs/CNFs, thus, appear to be among the most promising nanomaterials for enhancing the mechanical properties of cement-based materials and their resistance to crack propagation while providing such novel properties as electromagnetic field shielding and self-sensing.

Most research efforts have focused on CNTs compared to CNFs and have been performed on cement pastes. Only few investigations have dealt with incorporation of CNTs into mortar. One of the main challenges is the proper dispersion of CNTs/CNFs into cement paste, partly due to their high hydrophobicity and partly due to their strong self-attraction. These studies on CNTs/CNFs emphasize that resolving the issues related to dispersion and understanding the complexity of the fundamental mechanisms within the paste and the interactions at interfaces are key to optimizing the benefits of CNTs/CNFs addition to concrete.

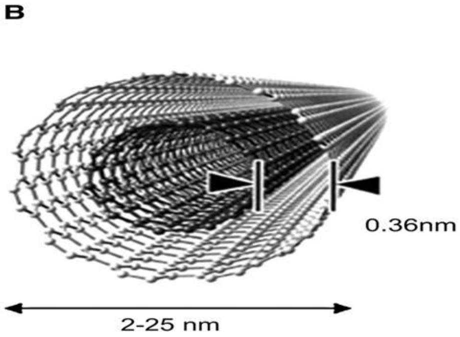


Fig. 4(b) multi walled carbon nanotube (MWCNT)

Out of the four types of concrete/materials discussed above, it can be understood that Nano Technology is a promising field for producing novel properties in concrete such as high compressive strength, High Flexural strength, High Ductility and Toughness. This field is showing a big prospect for infra-structure and sustainable development in future.

VII. OBSERVATIONS

To encourage greater implementation of new techniques in improving the ductility of concrete, general review points are summarized as given below

- ➢ The ductility of structures, in turn, depends on the ductility of individual components and structural configuration, including relative strength of different components and redundancy.
- ➢ A ductile concrete, with substantially higher tensile ductility compared to normal concrete, can contribute to higher structural resiliency and environmental sustainability, the latter by virtue of the need for less frequent repairs.

- The damage tolerant SHCC coupling beams are expected to undergo large shear deformation in a ductile mode with high energy-absorption capability.
- The innovation of Ductal ultra-high performance, fiber reinforced concrete (“UHPFRC”) is a revolutionary material that offers superior strength, durability, ductility and aesthetic design flexibility.
- By the introduction of UHPFRC there is almost no carbonation or penetration of chlorides and sulphides. The material has almost no shrinkage or creep, making it suitable for prestressed applications.
- Inclusion of Polyvinyl alcohol (PVA) in volume fraction of fibers from 1 to 2 %, increases splitting tensile strength with age.
- Inclusion of 5 to 10 % Metakaolin (MK) caused 16.5 % and 24 % increase in splitting tensile strength at age of 28 days as compared to control.
- 5% MK together with PVA fibers has higher splitting tensile strength with PVA fibers having aspect ratio 45, 60, and 90 with 2% volume fraction.
- Improving the Ductility of Concrete as a whole, rather than providing reinforcement at critical locations, will address the problem in more rationale way.
- Out of the four types of concrete/materials discussed above, it can be understood that Nano Technology is a promising field for producing novel properties in concrete such as high compressive strength, High Flexural strength, High Ductility and Toughness

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