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Future fighting vehicles will require lighter, stronger and more space efficient armor for better protection, survivability and greater mobility.

The invented lightweight armor component consists of armor-grade materials (2L such as ceramic, enclosed in fiber reinforced cementitious composite (FRCC) (1). The FRCC is used to substantially confine and pre-stress the armor-grade materials.

The resulting armor component of the present invention can provide excellent ballistic protection against all types and sizes of Kinetic Energy (KE) threats and Chemical Energy (CE) threats.

The armor component has low areal density, reduced damage area, improved multi-hit capability, flexible design and also provides high structural strength. It furthermore has the advantage that it can be formed in virtually any shape.

This invention results in superior ballistic characteristics of a (passive) armor system. An object of the present invention is to increase penetration resistance of especially ceramic based armor, while lowering system weight.

Fortsættes ...

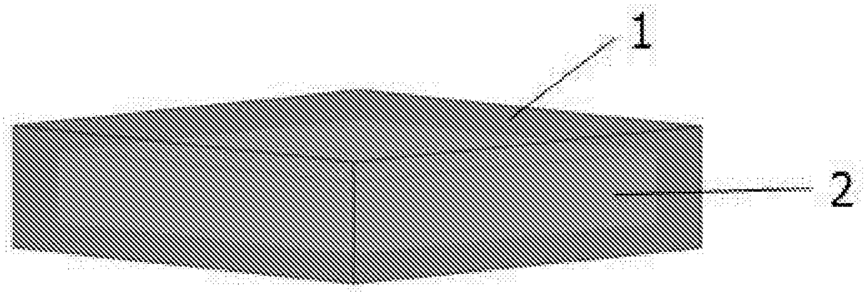

FIG 14

LIGHT WEIGHT COMPOSITE ARMOR WITH STRUCTURAL STRENGTH

Field of the invention

The present disclosure relates generally to passive ballistic armor for military and civilian use, and in particular, to lightweight composite armor structure with very strong structural strength based on a multi-material composite for absorbing and limiting the transfer of impact energy from most types and sizes of kinetic energy (KE) threats and chemical energy (CE) threats.

The present disclosure relates especially to ballistic protection for use in military vehicles of different types and other moving and stationary military platforms, or for use in permanent or temporary protection of different types in buildings or other fixed or mobile installations. The ballistic protection according to the present disclosure can be employed as protection against different types and sizes of low-velocity or high-velocity armor ballistic threats, such as armor piercing projectiles or threats based on chemical energy.

It is an object of the present disclosure to provide a composite armor that will prevent the penetration of projectiles in a structure while also providing structural support to the same structure.

Desired armor protection levels can usually be obtained if weight is not a consideration.

For over a century, metals have been the material of choice in providing load-bearing capabilities and ballistic protection for military platforms. Especially military vehicles have traditionally been manufactured from high strength armor plate steel.

Development of modern fighting technology, directed generally towards decreasing of mass of vehicles construction, creates simultaneously the necessity of increasing the penetration resistance of protective layers to all types of impact threats. Vehicles designed for land conflict are often lightly or inadequately protected from heavy machine gun (HMG) projectiles, high velocity kinetic energy-based anti-tank long rod penetrators (LRP), asymmetric threats such as fragments from Improvised Explosive Devices (IED’s), Explosively Formed Projectiles (EFP’s) and chemical energy threats (CE), which are all encountered with rising frequency by troops on operations.

The present disclosure provides an integral composite armor material for absorbing and dissipating kinetic energy from high-velocity armor piercing projectiles, IED's, EFP's as well as chemical energy threats such as RPG's. It is an improvement to existing ceramic-based armor.

The present disclosure improves upon existing composite armor designs through the use of Fiber Reinforced Cementitious Composite (FRCC), which is a composite material with a cementitious matrix and discontinuous reinforcement (short fibers), which are made of either inorganic or organic material, mostly steel fibers, polyvinyl alcohol (PVA) fibers and polyethylene (PE) fibers (FIG. 1).

More specifically, it relates to fully encapsulation and pre-stress of armor-grade materials, such as ceramics, with FRCC, providing armor with highly enhanced ballistic efficiency, physical durability, structural strength and environmental resistance.

The present disclosure results in superior ballistic characteristics of an armor system and can be ballistically qualified in different kind of shapes, sizes and thicknesses, and can be custom produced to meet any demand for ballistic protection. The overall shape of the panel will be determined by end user requirements. Often panels of the present disclosure will be generally flat and with generally uniform thickness. For more specialized end user requirements, a panel can be shaped in almost any form of curvature and varied thickness through the panel. The overall dimensions of the panels of the present disclosure will be determined by end user requirements, such as the impact conditions which they are required to resist, and the size and/or area of the object which the panel or an assembly of the panels is required to protect. These individual panels can then be laid into multiple-panel arrays to obtain broad area coverage of a contoured structure.

The transition between the different degrees of protection (light and heavier protection) can be implemented quickly and efficiently and upgrading/downgrading of existing protection can be performed quickly without particularly sophisticated equipment.

The result is a lightweight, composite hybrid structure for ballistic protection particularly suited to tactical ground vehicles. One advantage of the present disclosure is an increase in the ballistic penetration resistance of especially ceramic-based armor with a simultaneous decrease in the armor system weight. It also provides additional strong structural reinforcement.

Further areas of applicability will become apparent from the description provided herein. It should be understood that the description and specific examples are intended for purposes of illustration only and are not intended to limit the scope of the present disclosure.

Background of the invention

Ballistic armor is well known in the art as is herein detailed and described together with explanation why the prior art could be improved, or in some essential features is different from the present disclosure.

To defeat lethal projectiles, laminate systems composed of a hard frontal plate supported by a metallic or polymer composite backing are employed. In this system, the high hardness face plate breaks (shatters, erodes, blunts) the projectile defocusing the kinetic energy to allow the backing to effectively catch the residuals. In addition, the backing serves as a breadboard for attachment to the vehicle. This is employed in armor systems including dual hard steel, titanium-aluminum laminates and ceramic-composites. Facial ceramics are most effective in this type of application, but have limited fracture toughness and damage tolerance; thus the ceramic is parasitic to the vehicle structure.

There are two prevalent hard passive armor technologies in general use. The first and most traditional approach makes use of metals. The second approach uses ceramics. Each material has certain advantages and limitations. Metals are more ductile and are generally superior at withstanding multiple hits. However, they have a large weight penalty and are not as efficient at stopping armor-piercing threats. Ceramics are extraordinarily hard, strong in compression, light weight and brittle, making them efficient at eroding and shattering armor-piercing threats, but not as effective at withstanding multiple hits.

Light-weight metallic and ceramic armor designs are known. For example, metals such as titanium and aluminum alloys can replace traditional steel to cut weight. Ceramics, such as aluminum oxide, silicon carbide, and boron carbide, are used in combination with a supporting backing plate to achieve even lighter armor. When ceramics are employed in laminate constructions and are backed with high tensile strength, high-toughness “momentum trap” composites such as Kevlar or Spectra fibers, mass-efficient armor systems can be designed. The mass efficiency of such ceramic composite armor systems is generally two times (or more) higher than that associated with high hardness steel or similar high strength metallic armor plate.

State-of-the-art military armor systems for different platform protection frequently make use of lightweight, very high compressive strength ceramics such as silicon carbide (SiC), boron carbide (B_4C) or alumina as the so-called “strike face” of an armor laminate package. The purpose of the strike face material, as often employed in high performance ceramic composite armor systems, is to blunt and defeat incoming metallic projectiles by overmatching the compressive properties of the incoming projectile during the early (compressive shock) portions of the impact event. High modulus, high strength ceramics can have four to five times the dynamic compressive strength of projectile materials such as steel, tungsten or tungsten carbide. Thus, it is possible to shock the incoming projectile to the extent that compressive fracture is initiated. This decreases the ability of the projectile to defeat the armor system.

Armor-grade ceramics can be classified in three distinct material categories, a) Oxide ceramics such as alumina, zirconia, silica, aluminum silicate, magnesia, aluminum titanate and other metal oxide based materials, b) Non-oxide ceramics such as carbides, borides, nitrides and silicides, c) Composite ceramics, such as particulate reinforced ceramics, fiber-reinforced ceramics, ceramic-metal ceramics, nano-ceramics and combinations of oxide ceramics and non-oxide ceramics. Grinding of ceramics is part of the process of making ceramics suitable for high performance ceramic applications, such as armor applications and where tight tolerances are necessary.

An important ceramic material today for ballistic protection of military vehicles and ships is Alumina (Al2O3). Owing to its excellent price-efficiency ratio, alumina is the preeminent ceramic armor material for vehicular applications. When an extremely low weight is required (e.g. for personal protection or for helicopters), silicon and boron carbide materials are often used. Other ceramic materials may also be considered for the purpose of ballistic protection, Silicon nitride (SN), Titanium boride (TiB2), Aluminium nitride (AlN), SIALON (Silicon aluminium oxynitride), Fiber-reinforced ceramic (e.g. C-SiC) and Ceramic-metal composite materials (CMC).However, ceramic armor is not without serious engineering and practical shortcomings. High hardness, high elastic modulus ceramic materials such as SiC and B_4C are very brittle and have poor durability and resistance to dropping or even rough handling under field conditions. Furthermore, the low toughness of high performance ceramics implies that essentially all armor-grade ceramics have poor multiple hit capabilities. Once a ceramic tile is impacted, the subsequent impact response of the armor is seriously compromised.

Multiple hits are a serious problem with ceramic-based armors. Armor-grade ceramics are extremely hard, brittle materials, and after one impact of sufficient energy, the previously monolithic ceramic will fracture extensively, leaving many smaller pieces and a reduced ability to protect against subsequent hits in the same vicinity.

There are several sources of information which shows that confining the ceramics results in an increase in penetration resistance One relatively obvious and popular method to overcome the disintegration of ceramic armor is to encapsulate ceramic armor with a layer of surrounding metal.

In the laboratory, ceramics show much higher performance when their boundaries are heavily encapsulated. The problem is to devise methods to realize some or all of this encapsulation effect so it can be reduced to practical application in real armor systems. If the ceramic tile is not encapsulated, the fractured pieces can move away easily, and residual protection is lost.

State-of-the-art integral armor designs work by assembling arrays of armor-grade ceramic tiles/spheres/pellets within an encapsulation of polymer composite plating or metallic frames. Such an armor system will erode and shatter (armor-piercing) projectiles. Different designs are in current use over a range of applications. Substantial development efforts are ongoing with this type of armor, as it is known that its full capabilities are not being utilized.

There are several deficiencies with the encapsulation of ceramic material in the prior art. Because of the properties of the proposed metals, conventional casting processes cannot be readily and effectively utilized to encapsulate ceramic material. For example, the very high solidification shrinkage of metals precludes this process as the encapsulating metal exerts undue stresses on the ceramic material, and can result in the fracturing of the ceramic. Encapsulation of ceramic armor can also be performed by a number of other means, such as shrink-fitting ceramic tiles or bricks into metallic containers, or by other bonding methods involving the use of welded, bolted, brazed or adhesively bonded metallic containers. In the past, such layers have for instances been formed on or around ceramic material or tiles by techniques such as powder metallurgical-forming, diffusion bonding, and vacuum casting of liquid metal layers.

Accordingly, a need exists for an armor component formed of an encapsulated ceramic material that has improved penetration resistance, and for an inexpensive method for forming an armor component from a ceramic material that has improved penetration resistance.

Snedeker, et al. used a hybrid metal/ceramic approach in U.S. Pat. No. 5, 686, 689. Ceramic tiles were placed into individual cells of a metallic frame consisting of a backing plate and thin surrounding walls. A metallic cover was then welded over each cell, encasing the ceramic tiles.

More expensive encapsulation processes, such as, powder metallurgy techniques are used as disclosed in U.S. Pat. No. 4, 987, 033, which shows methods for metallic encapsulation of ceramic material with powdered metal layers that are cold isostatically pressed, vacuum sintered and then hot isostatically pressed to final density.

These methods have severe shape limitations, involve the use of relatively costly cold isostatic press tooling, requires a complicated and costly multiple step processing sequence, and still requires complicated and costly post-machining to produce a metallic encapsulating layer with consistent areal density. U.S. Pat. Nos. 3, 616, 115 and 7, 069, 836 respectively, shows methods for metallic encapsulation of ceramic armor based on vacuum hot pressing and/or diffusion bonding of ceramic tiles and metallic stiffening layers into machined arrays of lattice-type metallic frameworks. While capable of producing well-bonded and geometrically-consistent metallic encapsulation layers, these methods are also costly and very limited with regard to their shape-forming capability and the related ability to be transitioned to large-scale manufacturing, as they require expensive restraint tooling and die sets that essentially limit vacuum hot press or die pressing-based diffusion bonding to flat plate geometries.

Modifications of conventional liquid metal casting processes have been used as in U.S. Pat. No. 7, 157, 158. These methods, while capable of providing for encapsulation of different ceramic materials as well as complex shapes, require complex and costly molds, and the casting process itself presents many challenges since most metals of interest for encapsulation (Al, Mg, Ti etc.) shrink anywhere from about 3 to 12% upon solidification. The high coefficient of thermal expansion relative to armor-grade ceramics such as silicon carbide, boron carbide or alumina frequently leads to liquid metal casting-based encapsulation results generating very high stresses around the ceramic material, which can easily result in the fracturing of the ceramic being encapsulated. This situation would also be worsened for more complex ceramic armor tile geometries.

U.S. Pat. No. 5, 361, 678 issued to Roopchand reveals coated ceramic bodies in composite armor where the ceramic bodies are embedded in a metal matrix.

French patent No. 2526535 issued to Pequignot reveals ceramic elements embedded into a metallic plate and thermally stressed.

U.S. Pat. No. 6, 532, 857 issued to Shih reveals a ceramic array armor confined with shock isolated ceramic tiles with rubber between the tiles and over the top of them. Polysulfide is used as an encapsulation component.

U.S. Pat. No. 7, 117, 780 issued to Cohen reveals composite armor plate using a layer of pellets held by elastic material.

Object of the invention

The present disclosure is in the field of improved and lighter armor materials for military and civilian purposes.

“Smaller and lighter” is today’s paradigm for future combat vehicles. Passive armor is, and will be for many years to come, the last line of defense for vehicular survivability. Future fighting vehicles will require lighter and more efficient armor materials for greater survivability, mobility and transportability.

It is increasingly difficult to defend against the destructive forces of projectiles being produced and developed for the penetration and destruction of current armor materials. These projectiles are also here referred to as ballistic threats or simply "threats". Ballistic threats vary in size and type.

To meet these threats, exceptional mechanical and physical properties are required in armor materials. Toughened metal alloys, fiber reinforced plastics and high technology ceramic materials are some of the major armor materials used today. Other materials used in armor materials are glass, glass-ceramic and sintered refractory material. Many modern armors are multicomponent systems, using several plates of different materials bonded together in order to exploit the individual material properties to best advantage.

Ceramics like alumina, silicon carbide, boron carbide, beryllium oxide etc., represent one of the most important developments in armor materials. Their very high compressive strength and hardness, coupled with relatively low density, provide excellent armor performance against a wide range of high energy ballistic threats.

Ceramic armor materials are lighter than conventional metallic solutions, including titanium, and are two to three times harder. Use of ceramics lowers the weight of a passive armor system while improving the ability to defeat ballistic threats.

Ceramic materials have seen increasing use in ballistic applications where a combination of high compressive strength and low density are important. The very high compressive strength of ceramic materials offers the potential for more efficient destruction of penetrators than more conventional monolithic metals. However, the extreme localized loading of the ceramic during a ballistic impact often generates early failure and comminution of these brittle materials, and subsequent considerable loss of ballistic efficiency.

Ceramic materials are hard and brittle. The high hardness contributes to flatten the nose part of the incoming projectiles, which increases the forces to stop the projectiles. Regardless of the ceramic material used, ceramic armor is damaged on impact, and this damage propagation affects the subsequent ceramic performance. This damage is caused by the activation of preexisting defects by the shear and tensile forces that are generated on impact on the ceramic.

The brittle properties of ceramics are not good for sustained defeating of projectiles, however, the damage zone forms due to this helps to distribute the impact force over a larger area. Another effect of brittleness of ceramic material is the long cracks usually expand from the point of hit due to bending. The long cracks and resulting small pieces of ceramic material are harmful for the defeat of projectiles, because not much constraint exist in-plane to keep the material in the damage zone and to contribute resistance forces.

Ceramics are usually employed in an armor system where backing and surround plates are utilized in an attempt to increase efficiency of the comminuted ceramic. Such attempts at backing or surrounding the ceramic with different materials have been met with mixed success, partly because the underlying principals who influence successful system design are not clearly understood. Engineering a better backing and/or surrounding that can enhance the performance of the ceramic, would lower its weight and space burden in a structural armor application.

Different factors (backing plate stiffness, ceramic compressive strength, ceramic/-encapsulation impedance mismatch, etc.) have been shown to be important contributors to the overall efficiency of the ceramic/ encapsulation system. The resulting behavior of the ceramic is a complicated combination of the integrated responses of the damaged and undamaged regions. Since ceramics is rarely, if ever, used as a stand-alone armor, the mechanical response of the entire system determines the degree to which the damage is generated and how well the damage is encapsulated.

Ceramics are currently the subject of intensive research and improvement. The field applications of ceramic armors, however, have been limited by especially the high material cost. Incorporation of ceramics in hybrid armor systems can result in significant weight reductions, and are an excellent prospect for next-generation energy absorbing systems for ballistic protection.The present disclosure relates to the encapsulation and pre-stress of armor-grade materials, such as ceramics, with fiber reinforced cementitous composites (FRCC). The characteristics of FRCC can be utilized to exert a highly beneficial compressive stress on a ceramic material. Such beneficial compressive stress makes the encapsulated material to defeat the projectiles much more effectively by delaying the formation of cracks in the ceramics.

The objectives of the present disclosure are as follows:

- Enhancement of hydrostatic encapsulation of a material made of armor-grade materials, such as ceramic, to increase dwell time for a projectile on the front face of the encapsulated material thus promoting mushrooming and defeat of anti-armor projectiles of any types and sizes.
- Enhancement of multiple hit penetration resistances for individual tiles, tile arrays or more complex shapes in which the encapsulated material is divided into.
- Enhancement of the durability and damage tolerance against physical abuse and routine handling for the inner brittle material by providing a robust container for individual tiles, tile arrays or more complex shapes.
- Providing a composite armor that will prevent the penetration of projectiles in a structure while also providing structural support to the same structure.

The present disclosure is a major improvement to current ceramic-based integral armor, which results in superior ballistic performance and survivability, multi-hit capability including reduced damaged area, lower areal density, more flexible design as well as strong structural strength.

Summary of the invention

It is to be understood that the following detailed description present embodiments of the present disclosure and are intended to provide an overview or framework for understanding the nature and character of the present disclosure as it is claimed. The accompanying drawings are included to provide a further understanding of the present disclosure and are incorporated into and constitute a part of this specification. The drawings illustrate different embodiments of the present disclosure and, together with the description, serve to explain the principles and operations of the present disclosure but not to limit the present disclosure to these descriptions only.

The main idea of the present disclosure is accomplished by forming fiber reinforced cementitious material around the perimeter of an encapsulated armor-grade material, especially ceramic, to encapsulate and pre-stress this encapsulated material to increase dwell time and avoiding the inner core from lateral expansion when impacted by a ballistic threat, such as a projectile or a fragment.

Fiber reinforced cementitious composite (FRCC) is a very universal term for all cementitious materials that are reinforced by any kind of fibers. FRCC is concrete containing fibrous material which increases its structural integrity. It contains short discrete fibers that are uniformly distributed and randomly oriented. Fibers are man-made, such as steel, titanium, glass, carbon, polymers or synthetic. The character of FRCC changes with varying concretes, fiber materials, geometries, distribution, orientation and densities.

Many different so called high performance materials have been developed. The considered materials in this disclosure to encapsulate ceramic materials are all cementitious composites reinforced by randomly oriented short discrete fibers. Adding fibers enhances the compressive, tensile and shear strengths, flexural toughness, durability and resistance to impact and penetration as well as resistance to plastic shrinkage cracking.

Concrete is widely used in structural engineering with its high compressive strength, low cost and abundant raw material. But normal strength concrete has some shortcomings, for example, shrinkage and cracking, low tensile and flexural strength, poor toughness, high brittleness, low shock resistance and so on, that restrict its applications. To overcome these deficiencies, additional materials are added to improve the performance of normal strength concrete.

Cementitious matrices such as concrete have low tensile strength and low strain capacity and therefore fails in a brittle manner. As a result, the mechanical behavior of the concrete is critically influenced by crack propagation. Concrete can exhibit failure through cracks which are developed due to brittleness. A more ductile material can be achieved by the use of fibers in the concrete.

The use of fibers in concrete to improve pre- and postcracking behavior has gained popularity, and several different fiber types and materials have been successfully used in concrete to improve its mechanical and physical properties.

Reinforcing fibers will stretch more than concrete under loading. Therefore, the composite system of fiber reinforced concrete is assumed to work as if it were unreinforced until it reaches its "first crack strength." It is from this point that the fiber reinforcing takes over and holds the concrete together. For fibers reinforcing, the maximum load carrying capacity is controlled by fibers pulling out of the composite. Some fibers are more "slippery" than others when used as reinforcing and will affect the toughness of the concrete product in which they are placed.

Many catastrophic failures of reinforced concrete structures subjected to impact are associated with the brittleness of concrete material in tension. Although a compressive stress wave is generated on the loading side of the structure by impact, it reflects as a tensile stress wave after hitting a free boundary on the back side of the structural element. In addition, the tensile strength of concrete is lower (by about an order of magnitude) than its compressive strength. Therefore, concrete tensile properties generally govern concrete failure under impact.

Concrete is considered a brittle material, primarily because of its low tensile strain capacity and poor fracture toughness. Concrete can be modified to perform in a more ductile form by the addition of randomly distributed discrete fibers in the concrete matrix.

Ductile concrete would be highly desirable to suppress the brittle failure modes and enhance the efficiency and performance of current design approaches. The most effective means of imparting ductility into concrete is by means of fiber reinforcement.

An extremely ductile fiber reinforced brittle matrix composite is of great value to protective structures that may be subjected to dynamic and/or impact loading. Compared to normal strength concrete and fiber reinforced concrete, a ductile concrete based composite has significant improved tensile strain capacity with strain hardening behavior, several hundred times higher than that of normal strength concrete and fiber reinforced concrete, even when subjected to impact loading (FIG. 2).

While the fracture toughness of concrete is significantly improved by fiber reinforcement, most fiber reinforced concrete still shows quasi-brittle post-peak tension-softening behavior under tensile load where the load decreases with the increase of crack opening. The tensile strain capacity therefore remains low, about the same as that of normal concrete. Significant efforts have been made to convert this quasi-brittle behavior of fiber reinforced concrete to ductile strain hardening behavior resembling ductile metal. In most instances, the approach is to increase the volume fraction of fiber as much as possible. As the fiber content exceeds a certain value, normally 4-10% depending on fiber type and interfacial properties, the conventional fiber reinforced concrete may exhibit moderate strain hardening behavior.

The typical stress-elongation response of FRCC indicate two properties of interest, the stress at cracking and the maximum post-cracking stress (FIG. 3). While the cracking strength of the composite is primarily influenced by the strength of the matrix, the post-cracking strength is solely dependent on the fiber reinforcing parameters and the bond at the fiber-matrix interface. Thus, improving the post-cracking strength is the key to the success of the composite.

Special types of concrete are those with out-of-the-ordinary properties or those produced by unusual techniques. Concrete is by definition a composite material consisting essentially of a binding medium and aggregate particles, and it can take many forms.

The first fiber reinforced cementitious material that was developed in the early 1960s is steel fiber reinforced concrete (SFRC). SFRCs exhibit ductile behavior compared to the brittle matrix, but their flexural and tensile strengths are not very high, and especially the compressive strengths of these materials do not practically change with the fiber volume fraction. Although it shows certain improvements compared to normal concrete, it is not considered to be a high performance material. SFRC consists of a normal strength concrete matrix containing fine and coarse aggregates, which is reinforced by relatively long straight steel fibers. The primary improvements of traditional SFRC compared to normal strength concrete are a higher toughness and energy absorption capacity, greater spalling and delaminating resistance, improved durability characteristics through better crack control, as well as a higher ductility on a material level. Compared to normal strength concrete the tensile strength of SFRC is not improved significantly and SFRC still exhibits "quasi-brittle" failure (no strain hardening). The reasons for this are that low amounts of fibers are used, that the used fibers are relatively long and that the matrix contains too much course aggregate. However, compared to unreinforced concrete the failure is more ductile exhibiting a smother softening behavior.

Originally fiber reinforced materials, straight steel fibers at relatively low volume contents were used to improve the mechanical properties of traditional concrete. The addition of larger volume contents of fibers was mainly prevented by workability problems. In order to improve workability and restrict "balling" of fibers, the quantity of cement was increased and the amount of coarse aggregate reduced. Further improvement of workability could be achieved by the introduction of high-range water-reducing admixtures. Hereby the possible volume content of fibers could be increased. Together with the use of improved cementitious matrices with fewer coarse aggregate and carefully adjusted properties, this finally leads to the high performance fiber reinforced materials we know today.

FRCC includes the entire class of fiber reinforced cementitious composites (FIG. 4), and comprises fiber reinforced concrete (FRC), fiber reinforced mortar (FRM), high performance fiber reinforced composite (HPFRCC) and ductile fiber reinforced cementitious composite (DFRCC). DFRCC is a broader class of materials than HPFRCC.

Examples of modern high performance materials are engineered cementitious composites (ECC), sometimes also called “Bendable Concrete”, hybrid fiber concretes (HFC), multi-scale fiber reinforced cementitious composites (MSFRCC), compact reinforced composites (CRC) and reactive powder concretes (RPC), non-high performance fiber reinforced concrete and steel fiber reinforced concrete (SFRC).

Considering the mechanical properties of FRCC, these composites can be categorized into two classes: quasi-brittle and pseudo strain-hardening. Conventional FRCC fall into the first category whereas HPFRCC fall into the latter.

Quasi-brittle materials, such as normal strength concrete and conventional FRCC, usually fail due to the formation of a single macro-crack, whereas pseudo strain-hardening cementitious materials such as HPFRCC undergo multiple cracking. For conventional FRCC, the typical upper limit for fiber volume fraction is 3%. For such relatively low fiber content, the fibers mainly enhance the crack arresting ability, post cracking ductility, fatigue and impact resistance. The stress at first crack, maximum stress and the corresponding strain are not significantly improved compared to normal strength concrete.

HPFRCC show a large improvement in both strength and toughness compared with the normal strength matrix. The main feature of these materials is the optimum combination of strength and toughness which approaches the structural properties of steel.

HPFRCC is a generic term encompassing many different materials ranging from those that employ ultra-compact matrices and those that do not. However, the common point of all HPFRCC materials is their hardening tensile behavior that helps control cracking to a much better extent than usual FRCC.

The criterion which separates a HPFRCC from a traditional FRCC, such as SFRC, is its response in tension. If the material is strain hardening in the inelastic regime it is considered to be a HPFRCC. The fundamental difference between composites that show strain hardening and those who don't is that the ductility of the latter is only effective on a material level and does not affect the overall structural ductility. Or in other words the material does react in a ductile manner, but because it is softening in tension, the plastic deformations are restricted to a small area, resulting in damage localization and failure in a small zone with large crack openings. On a structural level this kind of ductility has little influence since the failure occurs locally and the rest of the structure remains elastic. Strain hardening fiber reinforced cementitious composites on the other hand retard localization and lead to multiple cracking and structural ductility even without the addition of structural reinforcement bars. For this reason they are called high performance fiber reinforced cementitious composites.

Because several specific formulas are included in the HPFRCC class, their physical compositions vary considerably. However, most HPFRCCs include at least the following ingredients: fine aggregates, a superplasticizer, polymeric or metallic fibers, cement and water. Thus the principal difference between HPFRCC and typical concrete composition lies in HPFRCCs lack of coarse aggregates. Typically, a fine aggregate such as silica sand is used in HPFRCCs.

Ultra high performance fiber reinforced concrete (UHPFRC) is a relatively new cementitious material, which has been developed to give significantly higher material performance than normal strength concrete, FRC or ECC (FIG. 5). UHPFRCC denotes a subclass of FRCCs that encompasses a number of ultra high strength concretes that are reinforced with steel fibers.

Many UHPFRCCs are also HPFRCCs and therefore exhibit strain-hardening and multiple cracking in direct tension._UHPFRCC are a sub group of HPFRCC combining the ductility of strain hardening cementitious composites with the high compressive strength of DSP concrete. UHPFRCC is furthermore distinguished between other FRCCs as a material exhibiting strain hardening in tension, whereas other FRCCs may exhibit a hardening behavior in bending, but are characterized by strain softening in tension. UHPFRC have good potential for absorbing energy through flexure. Studies of this material under dynamic loading have shown an increase in the ultimate strength with increasing strain rate.

UHPFRC can be mixed and cast like normal strength concrete with no special facilities or handling. “Ultra high performance” refers principally to improved mechanical strength, fractural toughness and durability. A mix is designed to combine high cement content with a very low water/cement ratio. The selection of fine aggregates achieves maximisation of the particle packing density and minimises any localised non homogeneity. Post-set heat treatment at 90 degrees Celsius can be applied to further improve the microstructure. This process results in a very high compressive strength concrete, typically between 150–200 MPa. The addition of a high dosage of high tensile steel fibers, normally 13 mm in length and 0.2 mm in diameter, results in a high flexural tensile strength, typically between 25–50 MPa. This material also has a very high capacity to absorb damage, with fracture energy in the range 20,000–40,000 J/m2.

Fibers are incorporated in UHPFRC in order to enhance the fracture properties of the composite material. The additional role of fibers in UHPFRC, in comparison to the role of fibers in ordinary and in high strength fiber reinforced concrete, is to provide sufficient ductility of the material in tension without a decrease in stress. This is achieved by choosing the appropriate type and quantity of fibers. In recommendations for UHPFRC, minimal fiber strength is limited to 2000 MPa. Fibers used in UHPFRC are typically short, smooth and straight, while hooked fibers are more often used in high-strength or ordinary concretes. Required fiber geometry can be estimated based on the relationship between pullout force and fiber-breaking force. The resulting high-strength and energy absorbing properties of UHPFRC are far superior to those of normal concrete.

DFRCC is a broader class of materials than HPFRCC. HPFRCC is an FRCC that shows multiple cracking and strain hardening in tension, therefore in bending as well. On the other hand, DFRCC encompasses a group of FRCCs that exhibit multiple cracking in bending only, in addition to HPFRCCs. Multiple cracking leads to improvement in properties such as ductility, toughness, fracture energy, strain hardening, strain capacity and deformation capacity under tension, compression and bending. The advantage of DFRCCs is the increased toughness under tensile stress condition. Among a variety of DFRCCs, some DFRCCs achieve pure tension toughness and ductility that are comparable to those of metallic materials, while others show increased toughness only under flexural tension.

ECCs make up a particular type of HPFRCC. HPFRCC also includes Slurry-infiltrated Fibrous

Concrete (SIFCON) and Slurry-Infiltrated Mat Concrete (SIMCON).

ECC are ultra ductile fiber reinforced cementitious composite materials. ECC essentially consists of two components: fibers and a cementitious matrix. Using a micro-mechanical approach, fiber and matrix properties are adjusted in order to obtain the desired macroscopic material behavior. The most characteristic material property of ECC is its extremely ductile, strain-hardening-like behavior in the inelastic tensile regime. This behavior has been termed "pseudo-strain hardening" referring to the post-yield strain hardening usually exhibited by metals. Although the macroscopic performance of ECC in the inelastic regime is very similar to the strain hardening observed for metals, the responsible micromechanical mechanism is a completely different one, hence the term "pseudo". In metals strain hardening is a consequence of a change in the molecular structure, whereas in ECC it is produced by multiple cracking and bridging of the cracks by the incorporated fibers.

ECC is a special type of HPFRCC which has been microstructurally tailored based on micromechanics. The most obvious beneficial mechanical property of ECC is its extremely ductile response in tension. Experiments show, that tensile strains up to 6% can be reached before softening sets in. This means that structural elements made from ECC are able to bear very large imposed deformations proved durability characteristics through better crack control, as well as a higher ductility on a material level which are of interest for impact loading. Microstructure optimization allows ECC to be made with fiber content less than 2-3%. ECC deforms pseudo uniformly due to dense and fine multiple cracks (FIG. 6); therefore it shows deformation capacity comparable and compatible to that of steel. While conventional reinforced concrete members suffer from steel yielding at localized cracks, reinforced ECC members attain deformation compatibility and utilize the deformation capacity of steel to greater extent.

Depending on the matrix constitution, the fiber geometry and the bond properties between fibers and matrix, a certain minimal volume content of fibers is necessary to achieve the typical pseudo strain hardening behavior of ECC. If the fiber content is too low, quasi-brittle failure as it is exhibited by traditional fiber reinforced concrete will occur. In this case damage localization and softening will set in immediately after formation of the first crack. Therefore the fiber content is usually chosen just above the critical volume fraction which allows for the pseudo-strain hardening and ductile behavior, but without using excessive amounts of fibers. In general synthetic fibers such as UHMWPE (ultra high molecular weight polyethylene) or PVA (polyvinyl alcohol) fibers are used (FIG. 7). The difference between these two fiber types is, that UHMWPE fibers show little chemical bond with the cement matrix whereas the chemical bond strength between PVA fibers and matrix is considerable. Therefore untreated PVA fibers are not very adequate for pullout behavior and preliminary surface treatment of the PVA fibers might be necessary. The used fiber volume contents are usually somewhere between 0.5% and 4%. Typically the synthetic fibers in ECC have a higher aspect ratio (fiber length to fiber diameter) than steel fibers used in steel fiber reinforced concrete. Their interfacial bond strength on the other hand is usually lower. A high aspect ratio is essential in minimizing the fiber volume content necessary for the pseudo-strain hardening behavior. The cementitious matrix in ECC consists of a Portland cement paste or mortar. The addition of fly ash and microsilica is possible and often used (FIG. 8).

The function of the synthetic fibers in ECC is to lead to steady state cracking and multiple cracking of the composite. In turn these two mechanisms are responsible for the pseudo-strain hardening behavior and large strain capacity of ECC. In order to guarantee multiple cracking, the bridging stress that can be transmitted by the fibers has to be larger than the first cracking strength of the intact matrix. This condition is referred to as the strength criterion for multiple cracking.

In general no or little aggregate with a relatively small grain size is used for the cementitious matrix of ECC. The main reason for this is to keep the fracture toughness of the matrix low. Adding large amounts of aggregate would result in longer fracture path distances and by consequence a higher fracture toughness. Having a low fracture toughness is a further condition to obtain multiple cracking with moderate fiber volumes.

SIFCON, SIMCON: SIFCON is produced by infiltrating slurry into pre-placed steel fibers in a formwork, and due to the pre-placement of fibers, its fiber volume fraction can amount to 20% at maximum. The confining effect of numerous fibers yields high compressive strength reaching over 200 MPa, and the strong fiber bridging leads to tensile strain hardening behavior in some SIFCONs. The fracture energies of SIFCON's are about 1350 times that of normal strength concrete. SIMCON uses pre-placed fiber mat instead of steel fibers.

RPC's represent a new generation of concretes which utilizes reactive powder, and it is designed with optimal packing theory. It's cube strengths between 200 and 800 MPa, tensile strengths between 25 and 150 MPa, and unit weights of 2500 - 3000 kg/m3. The fracture energy of these materials can reach up to 40000 J/m2, as compared to 100 to 150 J/m2 for ordinary concretes. The fracture energies of RPCs are about 300 times that of normal strength concrete. The RPC microstructure has a more compact particle arrangement and is enhanced by the presence of the strongest cementitous hydrates as compared to HPC. RPCs are produced by using very fine sand, cement, silica fume, superplasticizer and short cut steel fibers. Their very low porosity gives them important durability and transport properties and makes them potentially suitable materials for storage of industrial wastes. These features are achieved by 1) precise gradation of the particles in the mixture to yield a matrix with optimum density, 2) reducing the maximum size of the particles for the homogeneity of the concrete, 3) reducing the amount of water in the concrete, 4) extensive use of the pozzolanic properties of highly refined silica fume, 5) optimum composition of all components, 6) the use of short cut steel fibers for ductility, 7) hardening under pressure and increased temperature, in order to reach very high strengths.

Ductal is a range of ultra high performance concrete (UHPFRC) with very high compressive strength and non-brittle tensile behavior offering compressive strength of 160 to 240 MPa and tensile strength of over 10 MPa and with true ductile behavior. Ductal is an inorganic composite material based on the concept of RPC. The properties are characterized by high strength, high durability and high flowability. Ductal is a cement based composite reinforced with steel fibers under the concept of high strength and high toughness. W/C ratio is in the region of 0.2. The sand used has a fine grading, with the largest grains not exceeding around 600 um in diameter. The addition of silica fume and optimized use of admixtures are both absolutely essential. Last but not least, the concrete is reinforced with metal fibers, which have also been optimized for several criteria, involving optimizing not only the behavior of the individual fibers, but also their interactions within the matrix. A content of 2% by volume of 13-15 mm long fibers with diameters of around 0.2 mm emerges as a good compromise. Calculating the mean spacing of these fibers in the matrix gives a result of around 1.6 mm. which is perfectly compatible with the sand grading used.

UHSCs or Ultra High Strength Concretes are concretes with a very densely packed matrix, which causes them to withstand high compressive loads. They usually contain large amounts of fly-ash and silica fume and can reach compressive strengths between 120 MPa and 250 MPa.

In FRCCs, fibers can be effective in arresting cracks at both macro and micro levels. Most of the strain hardening FRCC is limited to single fiber type.

Mono fiber composites containing high stiffness fibers normally show high ultimate strength, low strain capacity and small crack width properties, while those containing low stiffness fibers show low ultimate strength, high strain capacity and large crack width properties.

Recently hybrid fiber reinforced cementitious composites (HFRCC) exhibiting strain hardening behavior is also developed. In hybrid fiber composites, two or more different types of fibers are suitably combined to exploit their unique properties. The use of optimized combinations of two or more types of fibers in the same concrete mixture can produce a composite with better engineering properties than that of individual fibers. A hybrid composite, with proper volume ratio of high and low stiffness fibers, show simultaneous improvement in ultimate strength, strain capacity and crack width properties.

The hybridization of fibers in FRCC can be done in different ways, such as by combining different lengths, diameters, modulus and tensile strengths of fibers. Large macro fibers bridge the big cracks and provide toughness while small micro fibers enhance the response prior or just after the cracking. Micro fibers also improve the pull out response of macro fibers, thus produce composites with high strength and toughness.

Over the last three decades, high compressive strength concretes and high tensile ductility concretes have emerged as two distinct classes of concrete. Materials at the frontiers of both of these classes include very high strength concrete (VHSC) with compressive strength around 200 MPa, and engineered cementitious composites (ECC) with tensile ductility in the range of *3%-6%.* The development of these two concretes was based on two different design philosophies that targeted two different structural performances. VHSC and similar high strength concretes (RPC, Ductal, MDF and DSP) were designed to achieve size efficiency in structural members for very large structures and to provide additional strength safety margin for strategically critical and protective structures. ECC and similar high performance fiber reinforced cementitious composites (HPFRCCs) were developed to ensure ductility of structural elements and massive energy absorption in the face of extreme load displacement events such as earthquakes. However, the decoupled development of VHSC and ECC resulted in mutual exclusion of each other's desirable properties. VHSC is an order of magnitude less ductile than ECC, whereas the compressive strength of ECC is three to four times less than VHSC. A combination of high strength and high ductility in one concrete material is highly desirable.

Recently, there have been a few notable investigations on combining high compressive strength and high tensile ductility in one concrete with limited success. Some mechanical test results of ultra high performance - strain hardening cementitious composites (UHP-SHCC) shows average compressive strength of 96 MPa and tensile ductility of 3.3% at 14 days after casting. The development of another such material, ultra high performance - fiber reinforced composite (UHP-FRC) shows compressive strength of about 200 MPa and tensile ductility of 0.6%. Although both of these materials attempt to combine tensile ductility and compressive strength in one concrete, UHP-SHCC has a compressive strength that is only about half that of VHSC, and UHP-FRC has tensile ductility which is at least five times smaller than ECC.

Newly development of a new composite material, high strength - high ductility concrete (HSHDC), shows both the desirable properties of high compressive strength (similar to VHSC) and high tensile ductility (similar to ECC) and are integrated into a single composite material. This results in higher specific energy absorption (or composite toughness) in HSHDC as compared to any other material in the class of high performance cementitious composites. The micromechanics-based principles that guide the design of ECC, combined with a VHSC matrix, led to the development of HSHDC.

Due to controlled cracking enabled by micromechanical tailoring of the composite material, HSHDC exhibits high tensile ductility in spite of a high strength brittle matrix.

Specific energy (or composite toughness) of HSHDC, is calculated as the area under the stress-strain curve before attaining ultimate stress capacity. A comparison of other composite properties of HSHDC with other similar high performance concrete materials is shown in FIG. 9. It can here be observed, that the specific energy of HSHDC is the largest among all the materials presented, which is a result of the combination of high tensile strength and high tensile ductility. Such material behavior leads to high energy absorption, which is critical for structures to withstand extreme loading conditions.

Fibers used in FRCCs

The use of short fibers in concrete to improve pre- and post cracking behavior has gained popularity. The mechanical properties of fiber reinforced concrete depend on the type and the content of the added fibers. Several different fiber types and materials have been successfully used in concrete to improve its mechanical and physical properties. In often used fiber reinforced concrete steel and synthetic fibers are mainly used, although a great variety of fibers made of other materials exists. This is related to the strength and stiffness that is required of the desired fiber contribution.

Unlike continuous fiber composites, the external loads are not directly applied to the fibers in FRCC. The load applied to matrix materials is transferred to the fibers via fiber ends and the surfaces of fibers. As a consequence, the properties of FRCC greatly depend on fiber length and the diameter (i.e., fiber aspect ratio) of the fibers. Further, several factors such as fiber orientation, volume fraction, fiber spacing, fiber packing arrangement, and curing parameters also significantly influence the properties of FRCC.

Using micro and macro fibers of different mechanical, geometrical and physical properties reduces the brittleness of cementitious materials. Adding short needle-like fibers to cementitious matrices enhances their mechanical properties, particularly their toughness, ductility and energy absorbing capacity under impact. The fibers can and should be engineered to achieve optimal properties in terms of shape, size and mechanical properties, as well as compatibility with a given matrix. All fibers are made of either inorganic or organic material. The inorganic category includes materials such as metals, minerals, ceramic, carbon and glass. The list of organic fiber materials, on the other hand, seems to be limited only by the creativity of nature and the chemical industry. Nature still holds the record for the strongest fibers, which are spun by spiders. Other natural fibers include cellulose, silk and cotton. Manmade organic fibers include nylon, polypropylene, polyvinyl alcohol (PVA), polyethylene and aramid, among many others.

Materials used in fiber reinforcing can include acrylic, asbestos, cotton, glass, nylon, polyester, polyethylene, polypropylene, rayon, rockwool and steel. Of these, acid resistive glass and steel fibers have received the most attention. Plastic fibers have shown to be of little value in reinforcing concrete until only recently. Natural fibers are subject to alkali attack and are also determined to have little value. The premium fibers are graphite reinforced plastic fibers, which are nearly as strong as steel, lighter-weight and corrosion-proof. Some experiments have had promising early results with carbon nanotubes. Fiber (steel or "plastic" fibers) reinforced concrete is less expensive than hand-tied rebar, while still increasing the tensile strength many times.

Short fibers used in concrete can be characterized in different ways. First, according to the fiber material: natural organic (such as cellulose, sisal, jute, bamboo, etc.); natural mineral (such as asbestos, rockwool, etc.); man-made (such as steel, titanium, glass, carbon, polymers or synthetic, etc). Second, according to their physical/chemical properties: density, surface roughness, chemical stability, non-reactivity with the cement matrix, fire resistance or flammability, etc. Third, according to their mechanical properties: tensile strength, elastic modulus, stiffness, ductility, elongation to failure, surface adhesion property, etc.

Short fibers are mainly characterized by the material and its mechanical properties and by their geometry. Once a fiber type has been selected, an infinite combination of geometric properties related to its cross sectional shape, length, diameter or equivalent diameter and surface deformation can be selected. The cross section of the fiber can be flat, circular, rectangular, diamond, square, triangular or any other significant polygonal shape.

The effectiveness of fibers on the mechanical properties of brittle matrix varies with the geometrical, mechanical and physical properties of fibers. Fibers with surface roughness and large specific surface area develop good bond with the matrix due to, as a results, micro-cracking mechanism before the occurrence of peak load is arrested in the presence of fibers, and fibered concrete exhibits high value of peak load compared to normal strength concrete without fibers.

The properties of concrete matrix and of the fibers greatly influence the character and performance of FRCC. The properties of fibers which are of interest include fiber stiffness, bond between fiber and concrete matrix, fiber concentration, fiber geometry, fiber orientation, fiber distribution and fiber aspect ratio.

In order to be effective in concrete matrices, fibers must have the following properties: 1) a tensile strength significantly higher than that of the concrete (two to three orders of magnitude); 2) a bond strength with the concrete matrix preferably of the same order as or higher than the tensile strength of matrix; and 3) unless self-stressing is used through fiber reinforcement, an elastic modulus in tension significantly higher than that of the concrete matrix. The Poisson’s ratio and the coefficient of thermal expansion should preferably be of the same order for both the fiber and the matrix.

In relation to the elastic modulus, fibers are divided into two types, those where the elastic modulus of fibers is less than the elastic modulus of the matrix: i.e. cellulose fiber, polypropylene fiber, polyacrylonitrile fiber, etc.; and those where the elastic modulus of fibers is greater than the elastic modulus of the matrix: i.e. asbestos fibers, glass fiber, steel fiber, carbon fiber, aramid fiber, etc.

To develop bond with matrix, specific surface area and surface conditions of fiber play an important role. Increasing the average bond strength leads to a direct increase in the post cracking strength of the composite and other important properties as well, such as toughness and energy absorption capacity. The different bond components are adhesion, friction, mechanical and interlock. In some fibers the surface is etched or plasma treated to improve bond at the microscopic level.

To develop better bond between the fiber and the matrix, the fiber can be modified along its length by roughening its surface or by inducing mechanical deformations. Thus fibers can be smooth, indented, deformed, crimped, coiled, twisted, with end hooks, paddles, buttons, or other anchorage.

When micro-cracks are developed, the stress in fiber increases gradually with the increase of crack openings, and a stage of either pulling out from the matrix before the stress in fiber exceeds its tensile strength capacity will happen or a stage of breakage of fiber will happen if the fiber are not pulled out from the matrix before the stress in fiber exceeds its tensile strength capacity. In order to enable the transfer of force with a small crack opening and sustain tensile force without breaking, a high modulus of elasticity and high strengths are required.

To transfer the stress across the crack edges (bridging action of fibers), length of fiber compatible with maximum aggregate size is important. Interfacial transition zone between the aggregate and the cement paste is the weakest phase in the concrete. In order to bridge this zone and to get highest effect of fibers, length of the fiber and the diameter of the aggregate must be coherent with each other. To develop an efficient bridging action, fiber must be embedded into the matrix on both ends beyond the aggregate particles. For that, fiber length must be at least greater than 2 times maximum aggregate size. Also to get better efficiency, fiber length should be 2 to 3 times the maximum size of the coarse aggregate.

Ideally the amount of fibers and aspect ratio should be as large as possible to maximize the improvements in the mechanical properties.

The length and diameter of synthetic fibers vary greatly. Single filament fibers can be as little as 10 micrometers in diameter such as for Kevlar or carbon fibers, and as large as

0.8 mm such as with some polypropylene or poly-vinyl-alcohol (PVA) fibers. Generally in concrete applications, the aspect ratio, that is, the ratio of length over diameter or equivalent diameter, of very fine fibers exceeds 100 while that of courser fibers is less than 100. Most synthetic fibers (glass, carbon, kevlar) are round in cross section; flat synthetic fibers cut from plastic sheets and fibrillated are suitable when very low volume content is used.

Most common steel fibers are round in cross section, have a diameter ranging from 0.4 to 0.8 mm, and a length ranging from 25 to 60 mm. Their aspect ratio is generally less than 100, with a common range from 40 to 80.

Different types of steel fibers have been developed (FIG. 10). They differ in size, shape and surface structure. Such fibers have different mechanical properties such as tensile strength, grade of mechanical anchorage and capability of stress distribution and absorption). Hence they have different influence on concrete properties. Some other types of closed-loop steel fibers such as ring, annulus, or clip type fibers have also been used and shown to significantly enhance the toughness of concrete in compression.

SFRC with the ring-type steel fibers (RSFRC), fails by more energy consuming mechanisms other than fiber pullout, whereby significant improvements in flexural toughness is obtained as compared to that of SFRC with conventional straight steel fibers. Fiber–matrix interfacial bond strength is provided by a combination of adhesion, friction and mechanical interlocking. While the mechanical performance of traditional straight steel fibers relies on the fiber–matrix interfacial bond strength, ring-type steel fibers are mainly designed to mobilize fiber yielding rather than fiber pullout. Three different types of flexural failure mechanisms of RSFRC are involved: fiber rupture after yielding and cone-type concrete fracture and separation between ring-type steel fibers and concrete matrix. Toughness indices of RSFRC are affected by fiber contents, ring diameter and fiber diameter.

Due to the formulation of the mechanics of the composite, the fiber content in cement matrices is specified by volume fraction of the total composite. Because of fiber materials of different densities, the same volume fraction of fibers of different materials leads to different weight fractions of fibers. Fibers are purchased by weight, but mechanical properties of composites are based on volume fraction, not weight fraction of fibers. Typically a 1% volume fraction of steel fibers in normal-weight concrete amounts to about 80 kg/m3 of concrete; however, a 1% volume fraction of polypropylene fibers amounts to about only 9.2 kg/ m3.

A lightweight composite armor is disclosed wherein one or successive layers of discrete armor-grade objects, such as ceramic blocks, are encapsulated within a fiber reinforced cementitious composite (FRCC). The FRCC is used to (1) encapsulate the armor-grade material, (2) pre-stress the encapsulated armor-grade material.

Studies shows that better confining of armor-grade ceramic results in an increase in penetration resistance, and that ceramic yield much higher performance when their boundaries are heavily encapsulated, because if the ceramic material is not encapsulated, the fractured pieces can move away easily, and residual protection is lost.

The type of encapsulation can influence the ballistic efficiency of the ceramic based armor, and that “dwell” type defeat of penetrators can be achieved on the ceramic front surfaces. Two key parameters here are suppression of cracked tile expansion and putting the ceramic in an initial state of high compressive stress to delay or stop it from going into a state of tensile stress during impact. Tensile stresses are the cause of the premature failure in ceramic components, since in general ceramic have higher strength in compression than in tension.

The advantage of such compressive stresses on ceramic component is two-fold. First, the ceramic material will have a higher tensile strength and will be more effective in defeating the projectile, as the projectile will spend more time (and more energy) before it causes the ceramic component to develop cracks and failure. This can allow the disclosed composite structure to defeat projectiles with minor damage to the ceramic component and therefore will allow the structure to take multiple hits component can be preserved due to the relative high elastic strain limit of cementitious composites. Even though the effectiveness of the system will be reduced (in the case of formation of cracks in ceramic), the remaining compressive stresses will maintain some effectiveness of the ceramic for subsequent hits, and at the minimum will keep the un-cracked portion of ceramic in place to defeat the projectile and dissipate its energy.

Yiwang Bao etal (materials letters December 2002) reported substantial enhancement in projectile penetration resistance in encapsulated and pre-stressed ceramic material, and experimental results by Holmquist and Johnson (EDP Sciences 2003) also shows that pre-stressed ceramics does improve performance. Other sources shows that three dimensional stressing of ceramic provides a higher enhancement in the penetration resistance than a two dimensional stressing.There is a clear need to improve the impact and penetration resistance, ballistic efficiency and structural integrity of ceramic armor employed on a widespread basis in many types of armor systems. Over about the past twenty years, it has been discovered that the ballistic performance of ceramic armor is critically dependent on the specific design attributes and geometrical configuration of the entire armor system. In particular, it has been observed that enhanced destruction and fragmentation of an incoming projectile can be obtained by increasing the so-called “dwell” time of the projectile on the front face of the ceramic armor during the very early stages (the first 5-10 microseconds) of the ballistic impact event.

“Dwell,” the duration of projectile erosion without target penetration, is an indicator of the ceramic’s ballistic efficiency. Strategies to prolonging projectile dwell on ceramics include retarding damage and retaining dynamic toughness in the damaged state. Ceramic failure caused by excessive structural bending from ballistic loading is another possible limiting factor to improving ballistic performance. Improving ceramic armor can be obtained with improved structural support for the ceramics. Desirable attributes of a backing material include shock mitigation and high stiffness to resist bending.

In general, the longer the dwell time on the front face of the ceramic armor, the more completely the projectile can be attenuated and fragmented. Enhanced dwell time on the front face of the ceramic armor leads to a phenomenon that is called interface defeat, wherein the projectile face mushrooms radially outward without significant penetration in the thickness direction; this increases the projectile frontal area and thus decreases its subsequent ability to penetrate the (ceramic) armor (FIG. 11). If the interface defeat is not sufficient, there will be an initial dwell and subsequent penetration into the armor (FIG. 12).

The phenomenon of dwell is used to particular advantage in medium or heavy ceramic armor systems that are intended to defeat larger caliber high kinetic energy projectiles (12.7mm HMG and above). It has been found that physical encapsulation of ceramics such as B_4C, SiC or TiB_2 increases the dwell time and delays the lateral and axial spreading of the comminuted zone ahead of the projectile, thus increasing the ballistic efficiency of the ceramic.

There are several advantages to using FRCC as a surrounding material for ceramic material. One is the relative high “yield” strength of FRCC that can be utilized to constrain the ceramic material very effectively and impede the material's disintegration. When the armor package takes a hit, the ceramic material will tend to fracture and dimensionally expand due to opening cracks. In this situation, the surrounding FRCC will be forced to stretch out and the material's resistance to yielding will be an important factor in impeding the disintegration of the ceramic material. This constrain of the ceramic material when hit by an incoming projectile results in:

- Constraints of material to prevent material “flee” from the impact zone
- Improved hardness of ceramic to flatten the tip of projectile at the initial stage of impact
- Transference of impact force to surrounding and supporting materials
- Small damage zone
- Other aspects to defeat projectile by involving more materials in the impact zone

Terminology

Brittle A material is called *brittle* if it loose its tensile strength immediately after first cracking under uniaxial tension and is no longer able to resist any stress.

Cementitious materials The binding component of fiber reinforced cementitious composites. These are: cement, mortar or concrete.

Composite materials *(or composites for short)* Engineered materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct on a macroscopic level within the finished structure.

Concrete A construction material composed of cement (commonly Portland cement) as well as other materials such as fly ash and slag cement, aggregate (generally a coarse aggregate such as gravel, limestone, or granite, plus a fine aggregate such as sand), water, and chemical admixtures. It is known as normal concrete, but also called normal weight concrete or normal strength concrete. DFRCC Stands for a subclass of FRCCs called *ductile fiber reinforced cementitious composites* which are hardening under flexural conditions (deflection-hardening) but not strain-hardening in direct tension (see also HPFRCC). The expression *ductile* emphasizes the fact that these composites exhibit multiple cracking which can be considered to be a form of ductility.

Ductile A *ductile* material is a material that does not fail immediately under uniaxial tension after reaching its first cracking strength. It first enters a strain-hardening phase, which is then followed by a crack opening phase and localization of failure.

FRCC Stands for fiber reinforced cementitious composites and describes cementitious materials that are reinforced by randomly oriented short fibers.

Glass An amorphous (non-crystalline) solid material. Glasses are typically brittle and optically transparent. In science, however, the term glass is usually defined in a much wider sense, including every solid that possesses a non-crystalline (i.e., amorphous) structure and that exhibits a glass transition when heated towards the liquid state. In this wider sense, glasses can be made of quite different classes of materials: metallic alloys, ionic melts, aqueous solutions, molecular liquids, and polymers. Polymer glasses (acrylic glass, polycarbonate, polyethylene terephthalate) are a lighter alternative to traditional silica glasses.

Glass-ceramic Materials that share many properties with both non-crystalline glass and crystalline ceramics. They are formed as glass, and then partially crystallized by heat treatment.

HPFRCC Stands for *high performance fiber reinforced cementitious composite.* It delimits a subclass of FRCCs which are strain-hardening in direct tension. It is also called *pseudo* strain-hardening or *quasi* strain-hardening. Strain-hardening refers to a true material property and should not be confounded with hardening due to a redistribution of internal stresses such as within the cross-section of a beam (referred to as deflection-hardening).

Localized Crack A *localized* crack is a crack at which the damage accumulates and where deformations start concentrating. It should be characterized by the crack opening displacement rather than a strain since the latter is gauge-dependent.

Multiple Cracking Means that a FRCC is capable of arresting the further opening of cracks by fiber bridging action and by consequence new cracks tend to form in the close vicinity. This is a fundamental property of HPFRCCs.

Quasi-Brittle The expression *quasi-brittle* describes a material that starts softening directly after first cracking under uniaxial tension. However, quasi-brittle materials are still capable of transferring some reduced amount of stress which gradually decreases with increasing crack opening.

Strain hardening / pseudo strain hardening Strain hardening describes a phenomenon that, under uniaxial tension, transmitted tensile stress increases successively even after first cracking, with continued tensile straining. The term “pseudo strain hardening” is sometimes used instead, since the strain hardening mechanism of DFRCC is different from that of metallic materials. During strain hardening/pseudo strain hardening, the stress-strain curve is uniquely defined, and is a true material property.

Strain softening Strain softening describes a phenomenon that, under uniaxial tension, transmitted tensile stress decreases upon first cracking or after strain hardening.

Structure A structure generally relates to the way elements are organized in relation to each other and relative to the whole they are in. This can be physical, spatial or systematically.

Tension toughness, compression toughness, flexure toughness Toughness describes energy absorption which is given by the area below stress-strain curve or load-displacement curve either in tension, compression, or flexure. In practice, toughness is calculated based on the area up to a prescribed strain or displacement.

Description of the figures

The accompanying drawings and photos, which are incorporated in and form a part of this specification, illustrates the technical background and embodiments of the present disclosure, and together with the description, serve to explain by way of example only, the principles of the present disclosure:

FIG 1 Illustrates the different compositions between normal strength concrete and UHPC;

FIG 2 A photo of a high strength - high ductility concrete (HSHDC) plate under bending;

FIG 3 Illustrates characteristics of cementitious materials: Definition of A: brittle, B: quasi brittle, and C: ductile behavior as well as strain softening and strain hardening under uniaxial tensile loading;

FIG 4 Illustrates some different high performance fiber reinforced cementitious materials and their classification;

FIG 5 Illustrates flexural performances of beam specimens made of different fiber reinforced cementitious materials;

FIG 6 Illustrates multiple cracking pattern of PVA-ECC under uniaxial tension;

FIG 7 Photos of polyethylene (PE) fibers and polyvinyl alcohol (PVA) fibers used in ECC;

FIG 8 Illustrates the composition of a typical ECC formulation and a concrete formulation, showing weight percent;

FIG 9 Illustrates and compares mechanical properties of HSHDC with other fiber reinforced cementitious materials;

FIG 10 A photo of typical profiles of steel fibers commonly used in some fiber reinforced concretes;

FIG 11 A photo of the sequence of three flash X-ray radiographs showing the initial dwell of a penetrator and subsequent penetration into thick ceramic target;

FIG 12 A photo of the sequence of three flash X-ray radiographs showing complete dwell of a penetrator on a thick ceramic target;

FIG 13 Photo collage of different forms and sizes of armor-grade ceramics, which can be used in the present disclosure;

FIG 14 A schematic cross-sectional perspective view of a first exemplary embodiment of the construction of a lightweight composite armor according to the present disclosure;

FIG 15 A schematic cross-sectional perspective view of a second exemplary embodiment of the construction of a lightweight composite armor according to the present disclosure;

FIG 16 A schematic cross-sectional perspective view of a third exemplary embodiment of the construction of a lightweight composite armor according to the present disclosure.

FIG 17 A schematic cross-sectional perspective view of a fourth exemplary embodiment of the construction of a lightweight composite armor according to the present disclosure;

FIG 18 A schematic cross-sectional perspective view of a fifth exemplary embodiment of the construction of a lightweight composite armor according to the present disclosure;

FIG 19 A schematic cross-sectional perspective front view of a sixth exemplary embodiment of the construction of a lightweight composite armor according to the present disclosure;

FIG 20 A schematic cross-sectional perspective back view of a sixth exemplary embodiment of the construction of a lightweight composite armor according to the present disclosure;

With reference now to the figures of certain preferred embodiments in detail, it is stressed that the particulars shown are by way of example and for purposes of illustrative discussion of the preferred embodiments of the present disclosure only, and are presented in the cause of providing what is believed to be the most useful and readily understood description of the principles and conceptual aspects of the present disclosure. In this regard, no attempt is made to show structural details of the present disclosure in more detail than is necessary for a fundamental understanding of the present disclosure. Only a few examples of how the composite armor structure can be configured in different shapes, sizes and thicknesses, and in different configurations, and how the encapsulated armor-grade material can be configured and arranged in different spacious patterns are shown here.

The description taken with the drawings makes it apparent to those skilled in the art how the several forms of the present disclosure can be embodied in practice.

One preferred solution is feasible where “a one-piece entity” of the composite material encapsulate and somehow pre-stresses the armor-grade material, and another preferred solution is feasible where a plurality of pieces of the composite material act together to pre-stress the armor-grade material (such as by sandwiching it and squeezing it).

The first solution where the fiber reinforced cementitious composite material encapsulates some other material is feasible by embedding armor-grade materials into flowing not yet cured fiber reinforced cementious composite materal. Different examples are shown in figure 14 to figure 16.

The second solution is feasible with previous casted and cured fiber reinforced cementitious composite material encapsulating, sandwiching and squeezing armor-grade material. An example is shown in figure 17 to figure 20.

Referring to FIG 14, a cross-sectional perspective view of an embodiment of a ballistic structure showing an encapsulant (1) confining an armor-grade material (2) for absorbing and limiting the transfer of impact energy from a ballistic threat, such as a kinetic energy projectile.

The encapsulant is fabricated from a fiber reinforced cementitious composite having a lower tensile strength than the tensile strength of the encapsulated material.

The encapsulated material is preferably comprised of armor-grade ceramic material. But it must be understood that the principles of the present disclosure are applicable to any armor-grade materials such as glass, glass-ceramics, sintered refractory material, other armor-grade materials having high hardness or mixtures thereof.

The encapsulating structural layer (1) is configured to encapsulate the armor-grade material (2). In one embodiment, the encapsulating structural layer (1) pre-stresses the encapsulated material (2). Without pre-stress, at least simple mechanical contact or binding is needed.

Referring to FIG 15, in another embodiment of the present disclosure, the encapsulating layer of fiber reinforced cementitious composite and the encapsulated ceramic material can be layered in a laminated structure, where the alternating layers of ceramic material and fiber reinforced cementitious composite are composed as shown.

Referring to FIG 16, in another embodiment of the present disclosure, the encapsulated ceramic material are formed as spheres and are all held and fully encased with an encapsulating layer of fiber reinforced cementitious composite. The gaps between adjacent ceramic spheres are made to be small enough for avoiding the creation of a weak point and stopping an anticipated projectile between the spheres.

Referring to FIG 17, in another embodiment of the present disclosure, the layer of fiber reinforced cementitious composite (1) encapsulates multiple tiles of armor-grade material (2); in this example four tiles are used.

Referring to FIG 18, in another embodiment of the present disclosure, two separate layers of fiber reinforced cementitious composite (2) and (3) encapsulates tiles of armor-grade material (4). Fastening elements (1) are used to obtain that the encapsulation layers of fiber reinforced cementitious composite provides pre-stress to the encapsulated armor-grade material.

Referring to FIG 19, in another embodiment of the present disclosure, two separate layers of fiber reinforced cementitious composite (1) and (2) and an additional layer of fiber reinforced cementitious composite (3) encapsulates armor-grade material. Fastening elements (4) are used to obtain that the encapsulation layers of fiber reinforced cementitious composite (1) and (2) provides pre-stress to the encapsulated armor-grade material. The additional layer of fiber reinforced cementitious composite (3) are configured to provide pre-stress to the encapsulated armor-grade material.

Referring to FIG 20, is the same embodiment of the present disclosure as referred to in figure 19, but is here shown in a cross-sectional perspective back view.

In any of the above embodiments of the present disclosure shown in FIG 14 to FIG 20, the thickness of the encapsulating layer can be varied as well as the dimensions of the encapsulated material can be varied.

Often panels of the present disclosure will be generally flat and with generally uniform thickness. For the purpose of constructing the panel, the front face is that which will face the direction from which the ballistic impact is expected, and the other is the back face. Likewise, the overall dimensions and the overall shape of the panels of the present disclosure will be determined by end user requirements, such as the impact conditions which they are required to resist, and the size and/or area of the object which the panel or an assembly of the panels is required to protect. For more specialized end user requirements, a panel can be shaped in mostly any form of curvature. Whatever its overall shape, the fact that it is a panel implies that its thickness will be smaller than its other dimensions, e.g. its length and width, and it will have two faces separated by its thickness.

The shapes shown in FIG 14 to FIG 20 are by way of example only. Other polygonal shapes can be used, such as cylinders and special shaped pellets. In addition, the shape of the tiles shown in FIG 14 and FIG 15 need not be a regular geometric shape. The tile can have any shape needed for a particular application, such as triangles, squares, rectangles, hexagons or combinations of polygons thereof, which nest to give complete coverage in one layer. In another configuration, polygon shaped tiles or combinations thereof are to be used in a first layer, and any gaps in the first layer are protected by a second layer to obtain complete coverage. It is most often desired to achieve complete coverage in one layer. Often used tile shapes used for this are square and hexagonal.

While the present disclosure has been described with reference to certain preferred embodiments, numerous changes, alterations and modifications to the described embodiments are possible without departing from the spirit and scope of the present disclosure, as defined in the appended claims and equivalents thereof.

Patentkrav

1. En struktur af sammensat panser til militær og civil brug til at absorbere og reducere effekten af anslagsenergien fra våbentrusler med kinetisk energi og fra våbentrusler med kemisk energi, nævnte struktur af sammensat panser omfatter:
Et kompositmateriale, der omfatter fiberforstærket cementholdigt kompositmateriale som indkapsler panserkvalitetsmateriale omfattende keramik, glas, glas-keramik og/eller sintret ildfast materiale.
2. En struktur af sammensat panser ifølge krav 1, hvor nævnte fiberforstærket cementholdigt kompositmateriale omfatter fiber reinforced concretes, fiber reinforced mortars, very high strength concretes, hybrid fiber reinforced cementitious composites, ductile fiber reinforced cementitious composites, ultra ductile fiber reinforced cementitious composites, high performance-strain hardening cementitious composites, ultra high performance-strain hardening cementitious composites, engineered cementitious composites og/eller high strength-high ductility concrete.
3. En struktur af sammensat panser ifølge krav 1, hvor nævnte panserkvalitetsmateriale af keramisk materiale er udvalgt fra en eller flere af følgende tre grupper, a) keramiske oxider, herunder alumina, zirconia, silica, aluminiumsilicat, magnesiumoxid, aluminium titanat og andre metal oxid baserede materialer, b) Non-oxide keramik, herunder karbider, borider, nitrider og silicider, og c) sammensatte keramikker, herunder partikelforstærket keramik, fiberforstærket keramik, keramisk-metal kompositmaterialer og nano-keramik.
4. En struktur af sammensat panser ifølge krav 1, hvor nævnte panserkvalitetsmateriale er anbragt i et rumligt mønster, i forskellige former, størrelser og tykkelser, og i forskellige konfigurationer og kombinationer.
5. En struktur af sammensat panser ifølge krav 1, hvor nævnte fiberforstærket cementholdigt kompositmateriale bliver konfigureret til forspænding af nævnte panserkvalitetsmateriale.
6. En struktur af sammensat panser ifølge krav 1, hvor nævnte panserkvalitetsmateriale er slebet og/eller uslebet.
7. En struktur af sammensat panser ifølge krav 1, hvor nævnte fiberforstærket cementholdigt kompositmateriale og nævnte panserkvalitetsmateriale er fastgjort til hinanden.
8. En struktur af sammensat panser ifølge krav 7, hvor nævnte fiberforstærket cementholdigt kompositmateriale er fastgjort til nævnte panserkvalitetsmateriale ved coating, limning og/eller fastgørelseselementer.

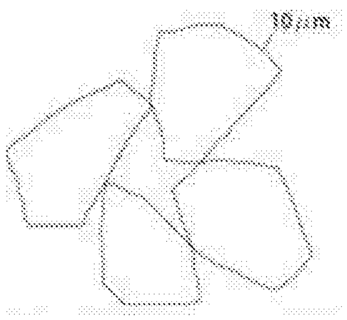

FIG 1A

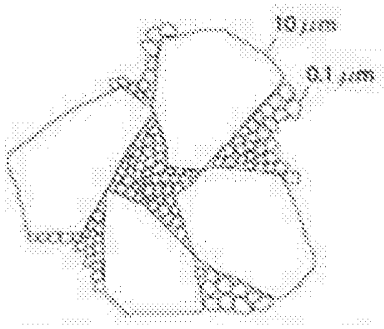

FIG 1B

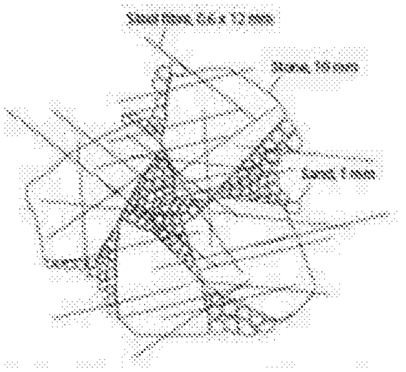

FIG 1C

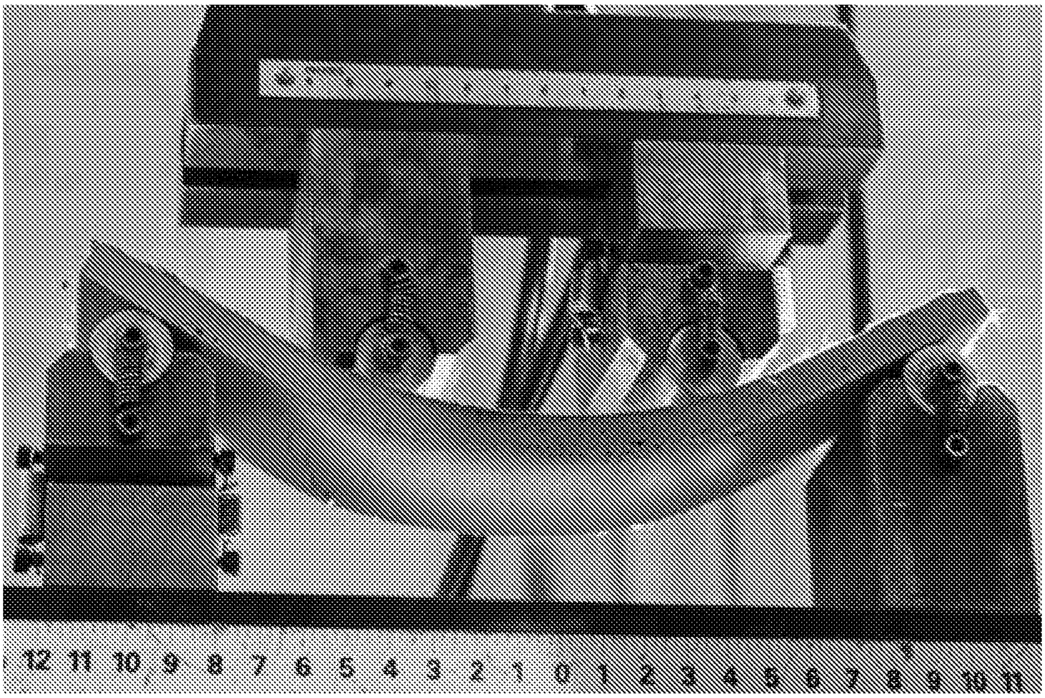

FIG 2

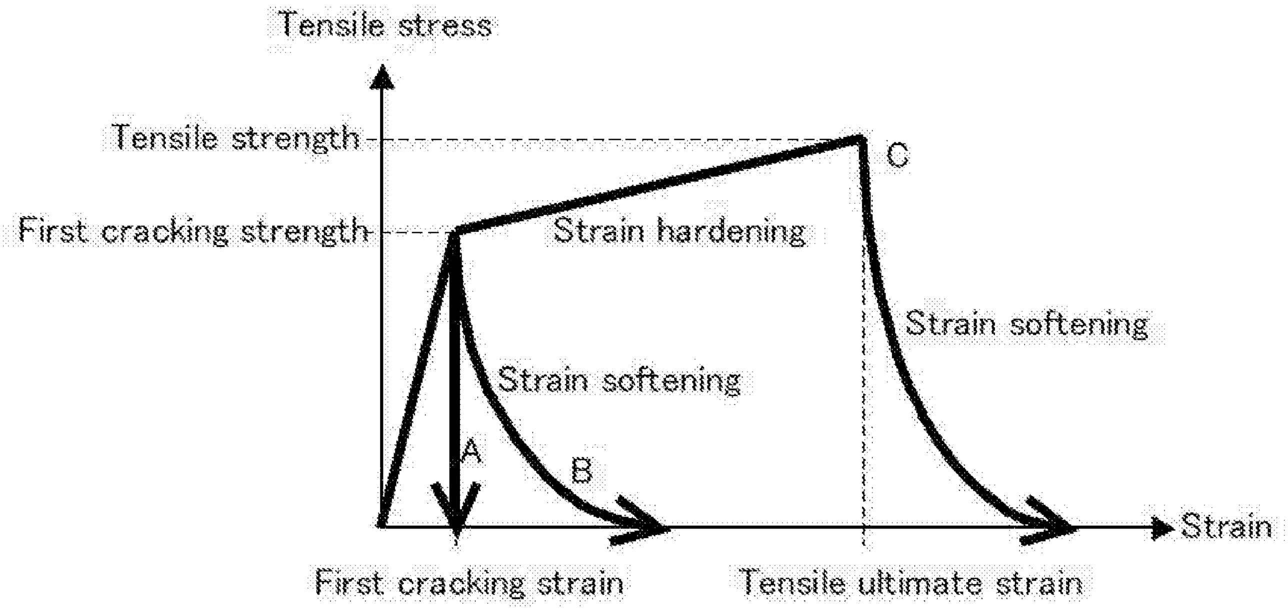
Tensile stress
Tensile strength
C
First cracking strength
Strain hardening
Strain softening
Strain softening
A
B
Strain
First cracking strain
Tensile ultimate strain

FIG 3

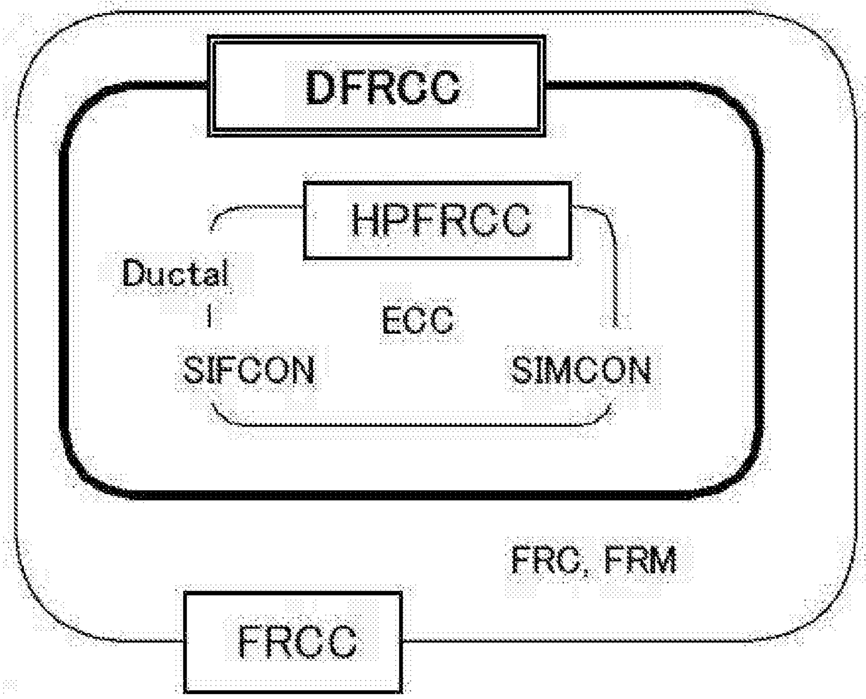
DFRCC
HPFRCC
Ductal
ECC
SIFCON
SIMCON
FRC, FRM
FRCC

FIG 4

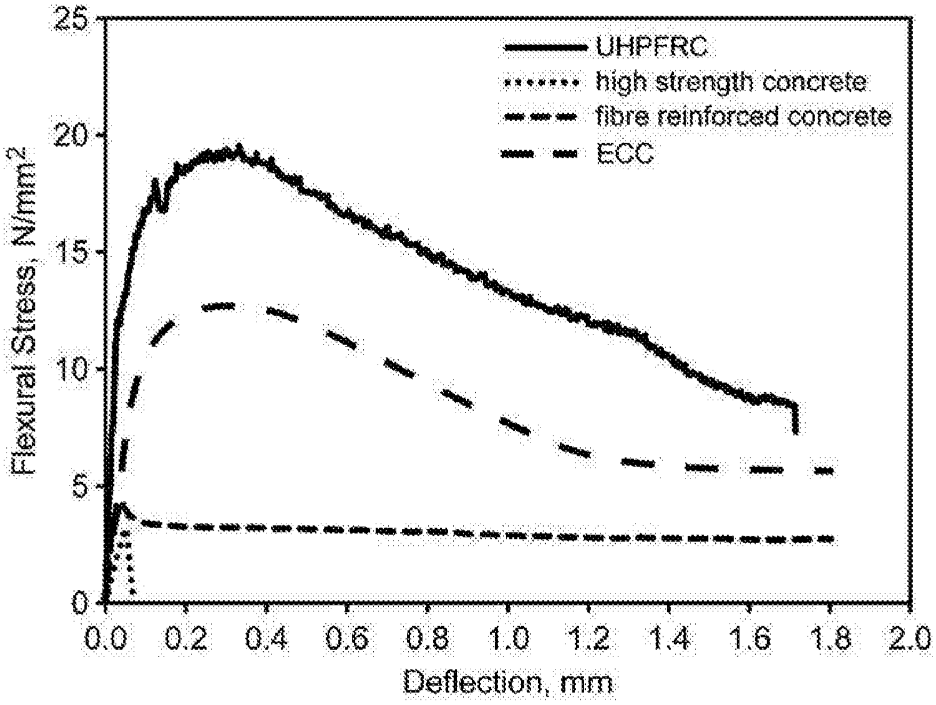
UHPFRC
high strength concrete
fibre reinforced concrete
ECC
Flexural Stress, N/mm^2
0
5
10
15
20
25
Deflection, mm
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

FIG 5

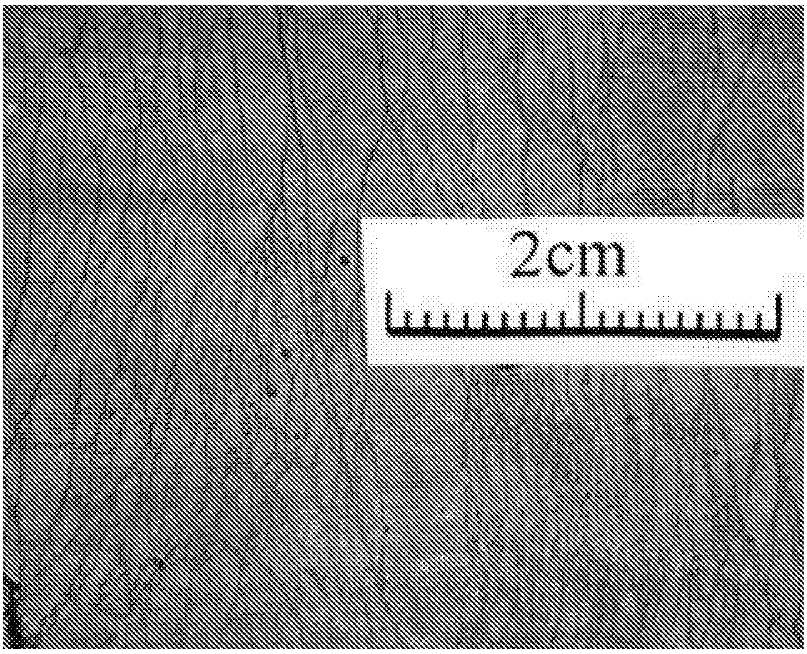
2cm

FIG 6

FIG 7A

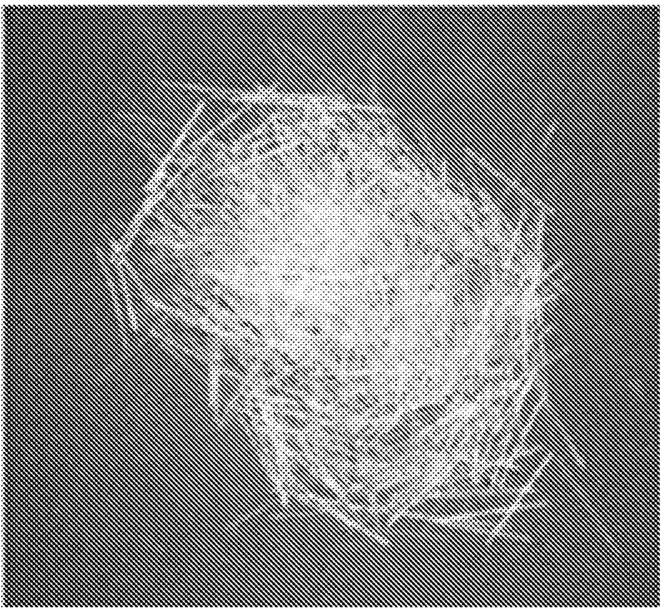

FIG 7B

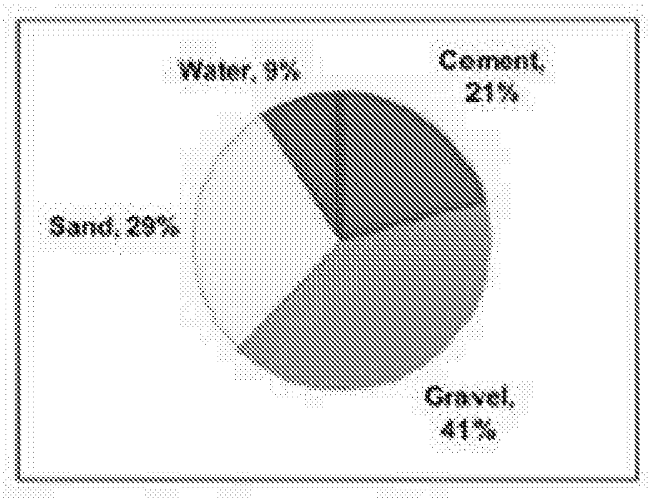

FIG 8A

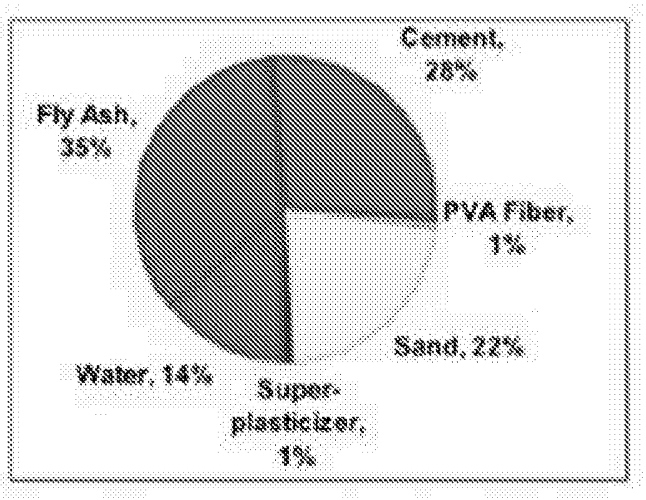

FIG 8B

Material	Comp. Strength f_c' (MPa)	First Crack Strength σ_{fc} (MPa)	Ultimate Strength σ_u (MPa)	Ultimate Strain* ε_u (%)	Elastic Modulus E (GPa)	Specific Energy SE (kJ/m^3)
VHSC	200	8.0	10.0	0.2	50	17
ECC	45	3.5	5.0	3.5	20	148
HSHDC	160	5.7	11.8	3.5	43	305
UHP-FRC	200	6.1	14.9	0.6	53	63
UHP-SHCC	96	6.0	11.0	2.7	32	228

FIG 9

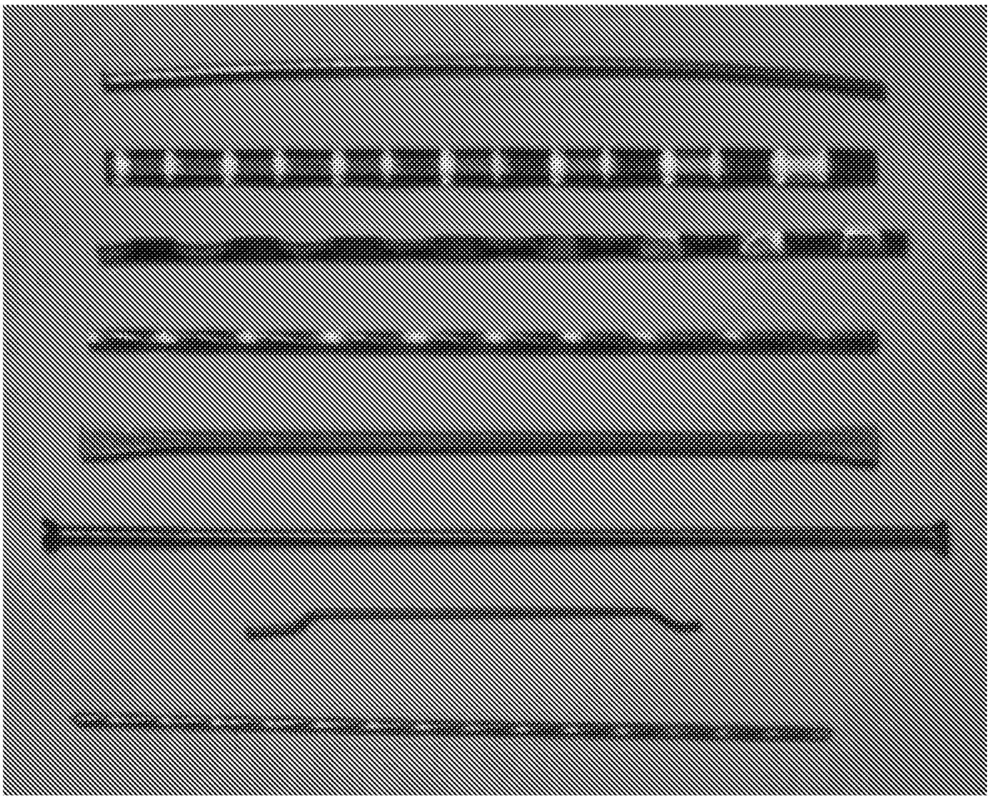

FIG 10

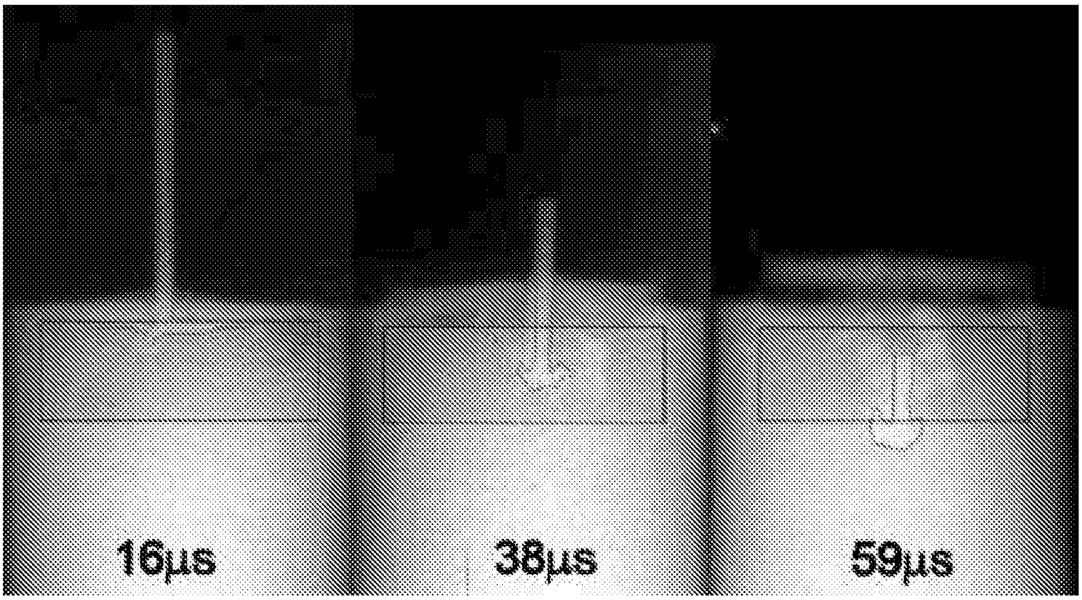

FIG 11

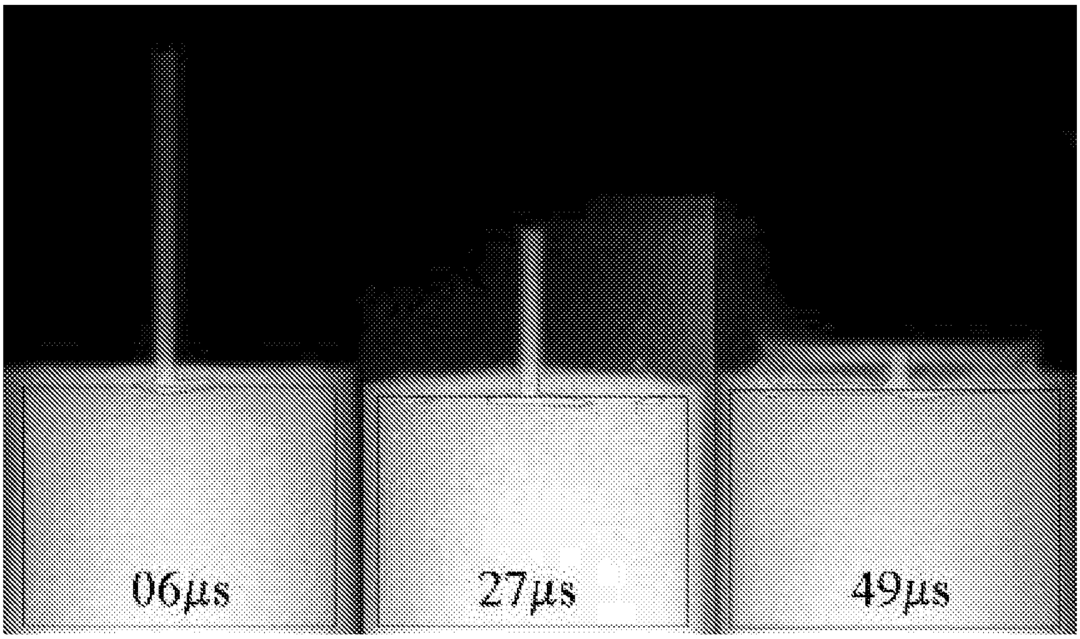

FIG 12

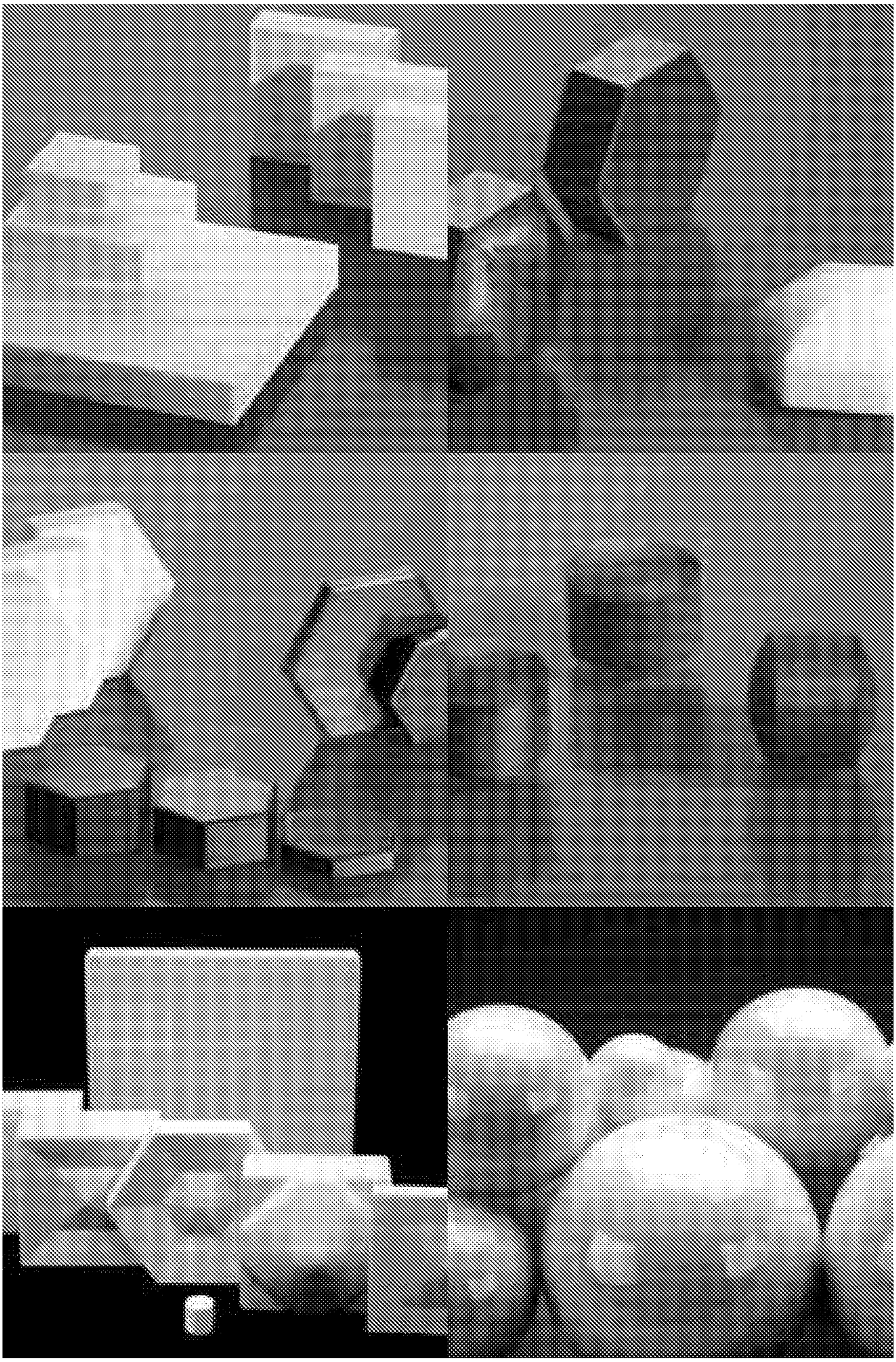

FIG 13

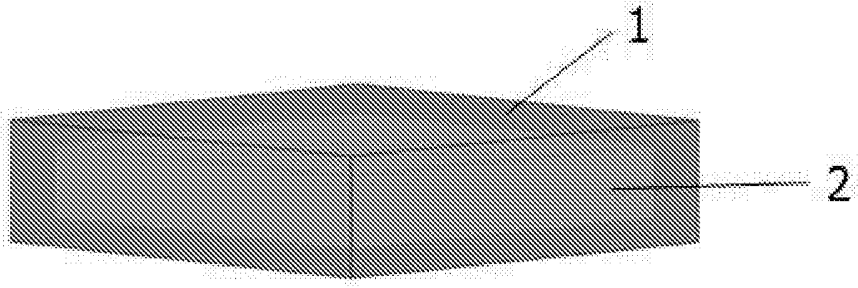

FIG 14

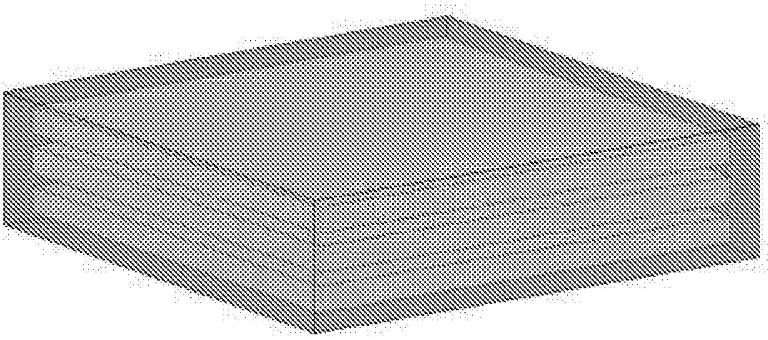

FIG 15

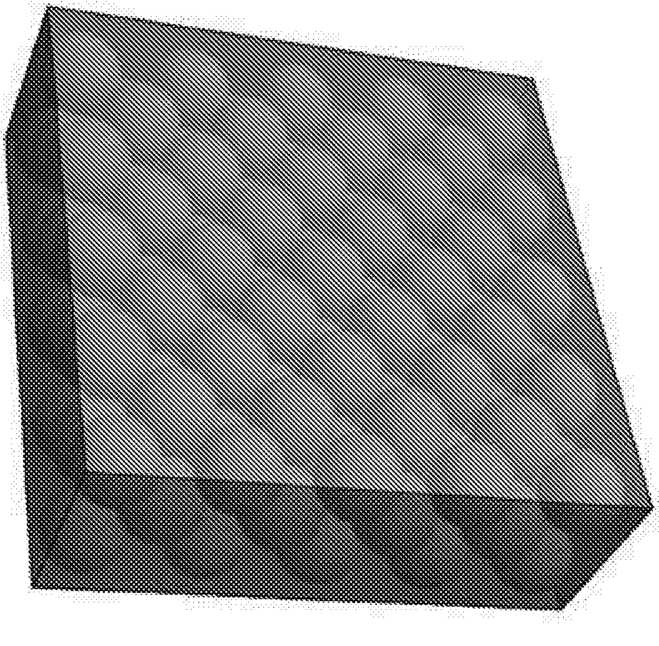

FIG 16

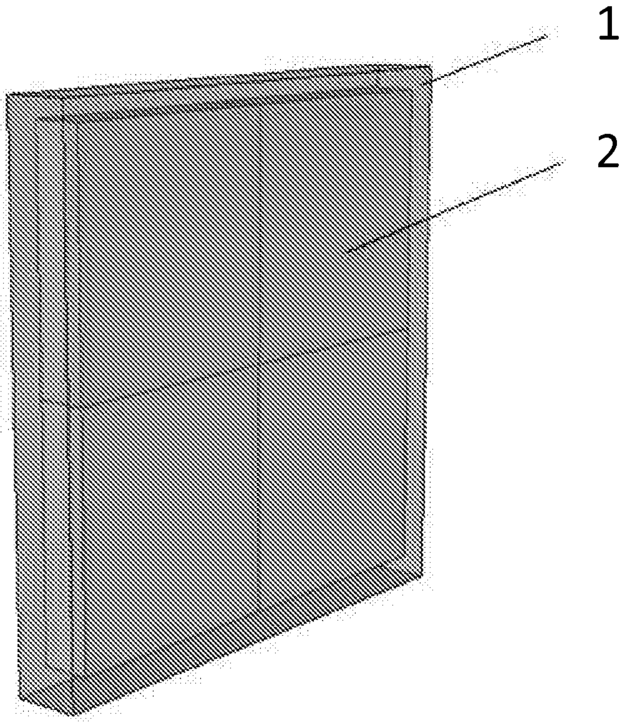

FIG 17

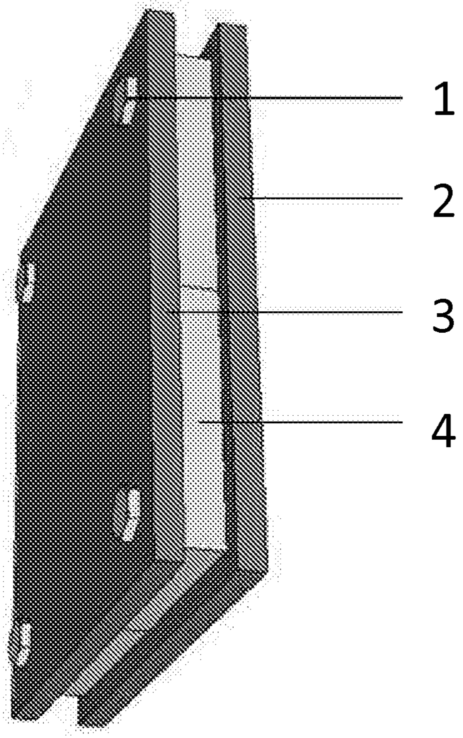

FIG 18

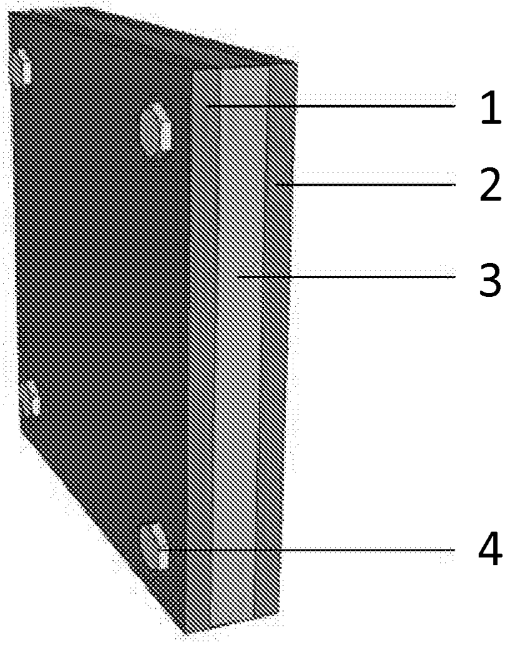

FIG 19

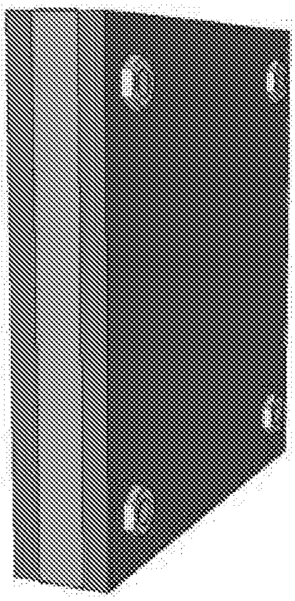

FIG 20