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Natural Fiber-Based Green Textile Reinforced Composites: A State-of-the-Art Review

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Abstract: In retrofitting, synthetic fibers are used as fiber-reinforced polymer composites (FRPs). Despite their good mechanical and thermal properties, FRP systems have a few disadvantages relative to natural fibers, such as high percentage of carbon dioxide emissions during manufacturing, problems with waste management, and high costs. A promising alternative to FRP is Natural Fiber Textile Reinforced Mortar (NFTRM), which consists of natural fiber grids embedded in a mortar to overcome the disadvantages of the FRP system. In many studies, natural fibers replace synthetic fibers in a textile reinforced mortar (TRM). In addition to being low-cost, lightweight, and eco-friendly, natural fibers offer superior mechanical strength and stiffness. The problem with natural fibers is that it carries hydroxyl groups on their superficial region, which becomes root cause for them to absorb more moisture than synthetic fibers. Natural fibers seemed to be studied to improve their strength, overall durability, and composite properties through various methods. The latest studies have the point of coverage on using natural fiber fabric-reinforced cementitious mortar systems for structural upgradation. As a part, the chemical composition, physical and mechanical properties of natural fibers, the causes of their hydrophilicity, their treatment, the tensile strength of their strands, and the composition of the mortar used as a matrix have been discussed. In addition, it discusses the testing of TRM composite under tensile load, parameters influencing the strength of TRM composites, a gripping system used to test TRM coupons, also the performance of structural members retrofitted with natural fiber textile-reinforced mortar.

***Keywords**:* Natural, Synthetic, Fiber, Textile reinforced mortar, Tensile strength, Composite.

Importance of the article

This review paper focuses on replacing synthetic fibers and polymers with natural fibers and green mortar, broadly referred to as textile reinforced mortar (TRM) composite systems for retrofitting and rehabilitation applications. It first provides an overview of TRM's constituents and material properties applications to retrofitting and tensile testing methodology. A summary of the mortar matrix composition for TRM composites is provided along with treatment to natural fibers. A discussion of mechanical properties of the TRM samples is also provided, including the parameters that affect their strength. In addition, the article emphasizes developing, extending, and exploring ideas using natural fibers and green mortar as natural fibers reinforced cementitious mortar is becoming more prevalent in engineering and construction as they are eco-friendly and contribute to sustainable development. The key objective is to convey to practicing engineers that natural fibers are also on par with synthetic fibers (glass fibers) with regard to strength and durability after proper treatment and can be put to use as alternative materials for retrofitting and rehabilitation applications in a sustainable and environmentally friendly manner. It is necessary to carry out extended research on the long-term reliability of Natural Fiber TRM composites, fatigue performance, bond behavior between natural fibers and mesh, and the development of standard methodologies for NFTRM composites.

Highlights

- Natural fibers are reviewed comprehensively in the context of TRM (Textile Reinforced Mortar).
- Natural fiber treatment is summarized.
- The mortar matrix composition for TRM composites is summarized.
- Tensile testing of TRM composites and gripping systems used by researchers are discussed.
- Investigations using TRM to strengthen the structural elements are highlighted.

1. Introduction

1.1 Background

There has been considerable interest in retrofitting and rehabilitating reinforced concrete (RC) structures by various methods over the past few decades [1]. Due to its high strength, fiber-reinforced polymer (FRP) is widely used for strengthening applications. However, in spite of its high strength, it exhibits several disadvantages, such as the high emission of carbon dioxide during the manufacturing process, the high cost, the inability to bond on a wet surface, and the use of epoxy resin as a substrate that is not heat and temperature resistant [2]. Therefore, finding an alternative technique for strengthening RC structures is necessary. To overcome the disadvantages of FRP, a recent technique known as fiber-reinforced cementitious mortar (FRCM) or textile-reinforced mortar (TRM) has been extensively examined. Using this system, natural or synthetic fibers are embedded in an inorganic mortar matrix, as shown in Figs. 1 and 2. Inorganic mortar matrix exhibits good fire and heat resistance and compatibility with reinforcement meshes[3]. As a result, TRM is suitable for strengthening and utilization in places that experience high temperatures and humidity, such as coastal areas. Several factors influence TRM performance, including the variety of fiber mesh used, whether synthetic or natural fiber, the strength of the mortar matrix, fiber geometry, reinforcement ratio, fiber orientation, the interface between fabric mesh and matrix, gripping system, the thickness of the mortar applied, the number of layers of fabric mesh utilized, mortar matrix composition, curing method, and other factors [4]. In TRM composites, natural or synthetic reinforcement meshes absorb the tensile load and arrest crack propagation. An inorganic cementitious matrix transfers the load uniformly to the entire composite system, improving its mechanical and durability performance.

There is possibility to alter the constituents of the mortar matrix to increase or decrease its strength. Micro silica, ground granulated blast furnace slag, Metakaolin, and alccofines are pozzolanic materials which can be added to mortar substrates to enhance their strength and durability. Agricultural, industrial, or construction waste can be used as filler materials in TRM mortar to increase the overall performance of the composite.

Karrar Al-Lami et al. examined synthetic fibers embedded in cement or lime-based materials, such as carbon, glass, and basalt fibers. This study examined the effects of textile coatings and stitch-bonded textiles on stress-strain responses. They concluded that textile coatings enhance the mechanical performance of textiles and allow a uniform redistribution of load between filaments and fiber bundles [5]. Using Basalt fiber-reinforced cementitious mortar as a masonry strengthening technique, Padalu et al. demonstrated a 4-fold increase in strength, 29-fold improvement in deformability, and 139-fold increase in energy absorption compared to unreinforced masonry wallets in terms of their energy absorption capacity [6]. In the Structural Engineering Research Centre, Chennai, India, Smitha Gopinath et al. developed a novel sandwich panel that combines TRC as the skin and profiled steel sheet as the core [7]. According to this study, the TRC sandwich panel could be made used as a floor panel. This floor panel was reinforced with carbon, aramid, alkali-resistant glass panels wrapped with knitted or woven textiles or bonded textiles or meshes.

In Comparison to the unstrengthen beam, the strengthened basalt FRC beam showed an enhanced ductility of 84.5 % and an increase in energy absorption of 162 % [8]. Smitha Gopinath et al. highlighted using precast TRC laminates in brick masonry strengthening, which displayed promising results compared to cast-in-place TRC laminates [9]. According to Andressa Cristine Hamillte Giese et al, textile layers, TRM age, and pre-cracking level affect the flexural behavior of strengthened beams [10]. Numerous studies have also been carried using synthetic fibers in TRM. Synthetic fibers, however, are not eco-friendly as they lead to the emission of greenhouse gases and global warming during their manufacturing process. Using synthetic fibers in TRM provides good strength and durability but is not sustainable. There by, recent studies are going on for substituting synthetic fibers by natural fibers in TRM. O A Cevellos et. al conducted work on sisal and flax natural fiber to study the effect of fabric parameters on tensile behavior and compared the performance with mineral fiber like glass fiber and concluded that fiber geometry and the volume fraction had greatest effect on tensile behavior of TRM composite (4). Giuseppe Ferrara r investigates the mechanical properties of a Textile-Reinforced Mortar (TRM) system produced with Flax textile embedded within a hydraulic lime-based mortar. This work aimed at studying the influence of reinforcement amount and the pretreatment given to natural fiber considered and concluded that feasibility of using flax textiles for strengthening and retrofitting of existing structures. (12) Hasan Assaedi studied on the influence of nano silica (NS) on the durability and mechanical performance of geopolymer composites that are reinforced with flax fabric and revealed that the addition of nano silica had a positive influence on the physical and mechanical properties of these composites. The presence of Nano Silica accelerated the geopolymer reaction and lowered the alkalinity of the system, thus reducing the degradation of flax fiber [14]. TRM using natural fibers, however, has been investigated much less frequently than TRM using synthetic fibers. The focus of research on making natural fibers water-repellent is due to their hydrophilic nature. A hydrophobic treatment is applied to the natural fibers pre incorporation into the TRM matrix. A previous work has shown that the performance of TRM composites obtained from natural fiber mesh is alike to that of TRM composites obtained from glass fiber mesh [11]. The TRM using natural fibers is extensively used in almost all the sectors like packaging, construction, aerospace engineering, mechanical engineering, retrofitting and rehabilitation with proper treatment to natural fibers.

As a result of the use of TRM as an alternative to FRP in structural upgrades, further studies are being conducted extensively. As compared to FRP composites, this area is still relatively underdeveloped. Mesh and mortar interfaces have not been deeply studied for their long-term and bond behavior. An overview of previous studies on natural fiber TRM composites and their structural applications is provided in this review.

An attempt is done to conduct a systematic review of the composition of TRM, A discussion of the different mortar matrixes employed by different researchers is also provided. The performance and behavior of TRM composites that incorporate natural reinforcing mesh are also examined. Studies aimed at structural upgrading using TRM have also been discussed.

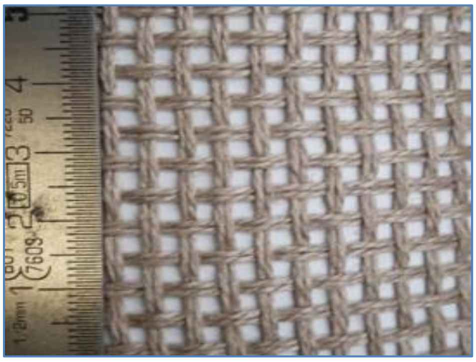

Fig. 1 Reinforcement with natural fiber mesh[15]

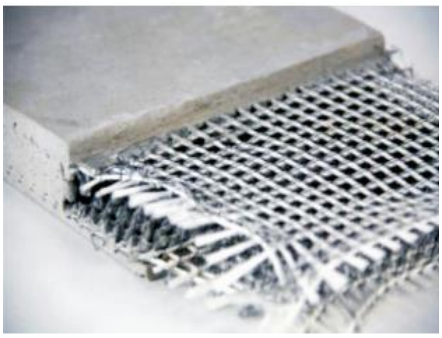

Fig. 2 Composite mortar reinforced with textiles (3)

2. Typical materials used in TRM composites

2.1 Natural fibers

In the recent times, many research is going on natural fibers as a sustainable construction material. There are many age-old caves made of natural fibers still existing and in working conditions. Researchers are very keen in studying the properties and behavior of that fibers utilized. Fibers such as sisal, hemp, flax, coir, jute can be used to reinforce mortar composites. Fiber yarns are made in the form of meshes with varying grid opening sizes, e.g., 5 mm, 10 mm, 15 mm, 20 mm, 25 mm, etc., based on their application and suitability, as depicted in Fig. 1. Though natural fibers offer some advantages, the problem with natural fibers is that it carries hydroxyl groups on their superficial region, which becomes root cause for them to absorb more moisture than synthetic fibers. Research is going on to improve the technical aspects and behavior of natural fibers to make them in par with synthetic fibers in all respect to natural fiber.

2.2 Natural fiber treatments

Natural fibers are low-cost, lightweight, environmentally friendly, and provide high mechanical strength and stiffness. Natural fibers, however, are susceptible to moisture absorption due to hydroxyl groups on their surface. Many earlier studies have given prominence on studying the problems associated with natural fibers and have handled them with different methods, thus increasing the strength and durability of natural fibers and composites. By providing proper treatment to natural fibers, Europe is leading in the field of utilizing natural fibers [18].

Various factors can contribute to the degradation of natural fibers, including ultraviolet radiation, dampness, humidity, temperature, or the occurrence and existence of microorganisms. The breakdown of hemicellulose, lignin, and cellulose in the fibers causes the degradation of fibers. The degradation of natural fibers can be seen in many different examples. After exposure to UV light for two years, Jute phenolic composites showed reduced elastic properties, swelling, pitch breaking, fibrillation, and dark spots. Surface treatment, chemical treatment, or coating of fibers was used to solve this problem [16]. During the chemical treatment, the hydroxyl groups are degraded and replaced with different reagents by grafting. Thus the presence of free radicals in the reagents, they can bind to OH groups, indicating a weak reaction with water molecules [17].

Several recent advances in chemical modification, the characterization of natural fibers, mechanisms underlying the latest trends in chemical modifications, were discussed by John et al. [18]. Their work indicates that the chemical treatment of natural fibers results in a covalent bond between the cellulose surface and the matrix. In order to improve fiber quality, surface treatments, such as solvent extraction and physio-chemical treatments, such as corona and plasma discharges or laser, gamma-ray, and UV bombardment, are applied. According to A. Valadez-Gonzalez different silane coupling agents affect the properties of henequen fiber-reinforced polymers [19]. Chemical treatments have been illustrated by Ali Abbas et al. involving alkali, salt treatment, mercerization, benzoylation, acrylation, titanium zirconate, maleated anhydride, grafted coupling agents, acrylonitrile grafting, triazine, permanganate, fungi, hornification and enzyme treatment, acetylation, cyanomethylation, isocyanate, esterification, etherification, bleach, pulp beating, and mechanical refining are some of the procedures.[17]. An epoxy coating can also be put into application to natural fibers. As a result, fibers are protected against alkali attack, mortar is prevented from coming into direct contact with fibers, good bonds are enhanced and promoted, and mechanical performance is improved. The polymer treatment of natural fibers improves their stiffness and strength. Horrification cause decrease in the cross-sectional area of fibers and improves their tensile strength. The alkali treatment, which involves immersing natural fibers in an alkaline solution like calcium hydroxide, positively impacts the bond between mortar and fiber. In Comparison to untreated banana fibers, banana fibers were given treatment with 1%, 3%, 5%, 7%, and 9% NaOH solutions. To examine the chemical composition of treated banana fibres, FTIR analysis was conducted. The morphological properties of the fibers were examined using SEM, and the thermal stability of the fibers was examined using TGA. The optimal dosage of NaOH was found to be 5%. A significant improvement in the interfacial characteristics of fibers, thermal resistance, and mechanical properties has also been observed [20].

It has been noticed that an alkaline environment causes the deterioration of natural fibers in a cementitious matrix. Adding nano silica particles to the composite containing flax fiber and geopolymer composites reduced the degradation of flax fibers in the geopolymer matrix [14]. Adding 30% metakaolin to the matrix and treating it with calcium hydroxide provides optimal protection for the fibers [21]. The results confirm that surface modification and chemical treatment can enhance the hydrophobic properties of natural fibers. Various surface, physical and chemical treatments can be applied to fibers to enhance their performance. The same treatment is applied regardless of whether the natural fiber is embedded in epoxy resin, cementitious mortar, pozzolanic mortar, or geopolymer mortar. A further study is required to determine whether the treated fibers behave differently when applied to epoxy resin or other cementitious mortars. Following the proper treatment of fibers, improved load-carrying capacity, reduced brittleness, improved durability, good cohesiveness, and improved bonding properties are expected.

2.3 Mortar substrate for TRM composite

TRM matrices have been developed to meet various requirements, including workability, good bonding to textiles, durability, etc. Cement is replaced with hydraulic or pozzolanic materials in a highly alkaline environment to prevent the fabric from degrading. By converting calcium hydroxide into the calcium-silicate-hydrate gel, pozzolanic material enhances the strength of mortars. The following are some of the mortar modifications that were used to embed natural fiber fabrics.

Ferrara et al.used hydraulic lime-based mortar to incorporate flax fiber fabric into NFTRM. Lime-based composite systems proved highly effective in strengthening and retrofitting existing masonry and concrete structures. Lime-based mortars contain a natural hydraulic lime binder and fine aggregate with a maximum nominal diameter of 1.19 mm. Due to the granulometric particle distribution, the mortar can penetrate the textile [22]. Cevallos et al. examined the tensile response of flax and sisal fiber mesh embedded in the hydraulic lime matrix. In this case, the matrix consisted of a lime-based grouting mix containing natural pozzolanas and carbonated filler. As a result of fiber mineralization and alkali attack due to humidity issues, the OPC matrix undergoes accelerated ageing. Therefore, using natural hydraulic lime (NHL) mortars ensures the absence of any OPC binder and, therefore, any water-soluble salts [4]. It has been indicated by Ardanuy et al. that the modification of the cementitious matrix is essential to enhancing TRM durability, and the formation of portlandite should be reduced by the addition of pozzolanic materials [23]. Fabio Longo et al. concluded that fabric-reinforced fly ash based geopolymer mortar and expanded glass aggregate performed better than conventional cement mortar [24]. As an alternative to conventional cement, metakaolin, micro silica, fly ash, GGBS, and stone powder can be made use to TRM mortar as a partial replacement for OPC. Due to the highly alkaline nature of cement, studies have been conducted to find alternatives to cement that offer less alkalinity and result in less degradation of natural fiber fabrics, for example, calcium aluminate cement, high alumina cement, inorganic phosphate cement, and geopolymer mortar. TRM mortar may also get the benefit from adding short fibers, which prevents cracks from forming and propagating.

It is also very important to note that the performance of the mortar matrix depends on the morphological characteristics of Engineered Cementitious Concrete. Sand with a lesser degree of roundness and sphericity is more likely to bond with a binder material, resulting in higher compressive strength. An enhanced or increased degree of fiber dispersion is observed with lower roundness, fine aggregates, and sphericity. Consequently, the tensile strength and interfacial bonds are enhanced [25]. It is imperative to consider both the design of the mortar matrix as well as the durability tests on the designed mortar matrix. Some of the durability tests performed on mortars are strength, water absorption, water penetration, rapid chloride penetration, thermal stability, dimension stability, expansion due to alkali-silica reaction, determination of alkali reactivity by mortar-bar method, resistance to rapid freezing and thawing, static modulus of elasticity, carbonation, corrosion resistance, etc. Thus, the strength and durability of the mortar mix greatly effects the compatibility and the structural performance of entire TRM composite.

3. Applications of natural fiber-reinforced cementitious composites (NFTRCCs)in structural upgradation

Composite materials consist of materials with different chemical and physical properties. However, combining the individual elements results in a material with properties different from those of the parent individual elements while taking advantage of their individual properties. The applications of these materials have been made use to almost all sectors, such as packaging, automotive, aerospace, and construction. FRP is a successful technique for structural upgrades in the building and construction industry. The structural strength of this FRP is excellent. It is crucial to note that using FRP is not eco-friendly as the production of synthetic fibers such as carbon, glass, aramid, basalt, and epoxy resins emit an enormous amount of carbon dioxide into the atmosphere, contributing to global warming. Therefore, the construction industry has stepped towards sustainable development to protect the environment and reduce carbon footprints. Consequently, FRP composites are being replaced with TRC mortar incorporating natural fibers. Natural fiber textile reinforced composite mortars (NFTRC) consist of natural fiber fabric mesh embedded in an inorganic cementitious substrate with the required grid spacing. The fabric mesh carries tensile loads, whereas the matrix transfers uniform stresses. Thus, the strength of the fiber fabric, the orientation, the number of layers of fiber mesh, the size of the grid opening, the strength of the mortar matrix, and the thickness of the mortar matrix impact the composite's total tensile load-carrying capacity. In Europe, NFTRC is extensively used in the construction industry. As shown in Fig. 3 and Fig 4, NFTRC has been successfully applied to structural upgradation. On the basis of requirements, TRM may be applied as a U-wrap, full wrap, or side wrap. The TRM technique is used for upgrading redundant flexural or shear members, as shown in Fig. 4 (3). A brief summary of some structural applications of NFTRC has been provided. Codispoti et al. examined jute, hemp, flax, and sisal TRM composites with inorganic substrates and concluded that the flax fiber TRM embedded in an inorganic substrate was the best choice for strengthening existing structures concerning strength and stiffness, in comparison to the all-natural fibers considered in the research study [26]. Ferrara et al. examined the performance of a bidirectional flax fiber TRM composite system. It has been demonstrated that the application of flax TRM as a strengthening material to masonry structures enhances their mechanical response under diagonal compression tests [13]. Bello et al. [27] claims that masonry structures can be strengthened using a cementitious matrix reinforced with sisal fibers. Using Jute TRM, Marques et al. reinforced masonry panels and concluded that further studies are required to comprehend long-term durability [28]. Niki Trochoutsou studied the tensile performance of lime-based natural fiber composites as a strengthening system for masonry. To upgrade the structure, they examined jute and flax TRMs, and obtained satisfactory results, demonstrating that flax TRMs with a denser mesh and a smaller diameter significantly outperformed jute TRMs [29]. TRM with flax fiber fabric in a hydraulic lime-based mortar was studied by Ferrara et al. [12], who concluded that flax could be used as a strengthening material with TRM. Because the fiber fabric carries all tensile loads, the performance of TRM depends on whether the fabric is unidirectional or bidirectional. Ferrara et al. [13] examined the shear strength of externally strengthened masonry walls using the Flax-TRM composite system. They observed a 118% increase in their shear capacity with one flax textile ply and 136% with two overlapping flax textile plies. Codispoti et al. evaluated the mechanical performance of natural fibers in retrofitting masonry structures. Fibers such as flax, hemp, jute, sisal, and coir have been investigated from a physical and mechanical perspective. To produce composites, the fiber with the best performance was tested with 3 different matrices (two of which were organic). While previous studies have provided information regarding the use of natural fiber TRM to upgrade structural elements, it is still necessary to conduct further studies to fully evaluate the durability, long-term behavior of natural fiber, and bond between structural members and composites. The tensile strength of composite members must be determined before applying TRM for any strengthening purpose. This can be accomplished by performing a tensile test on coupon specimens following the standards. The following sections provide detailed information regarding the tensile test of natural fiber composite coupons.

Fig. 3 The use of TRM to upgrade masonry [30]

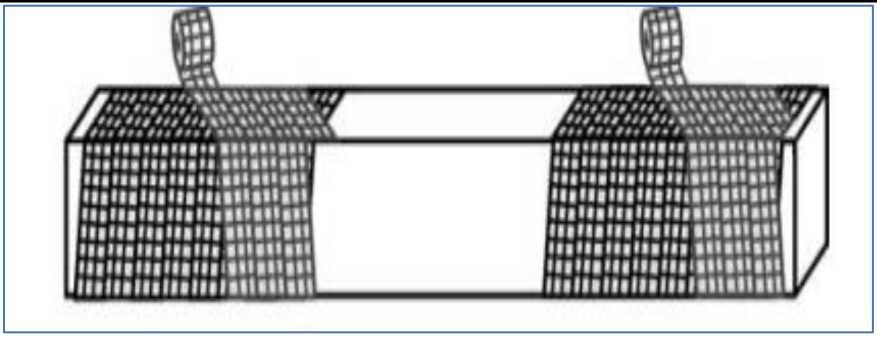

Fig. 4 Strengthening of beams using TRM [31]

4. NFTRM tensile test and response

4.1 Background

The earlier studies on the tensile behavior of TRM emphasize the importance of studying the tensile performance of the individual fiber strands, fabric mesh, and TRM composites. Fig. 5 exemplify the tensile testing setup used to inspect the behavior of a single strand and a fabric mesh. Tensile tests carried out on single fiber strands and fabric meshes can provide idea about the tensile load carried by the fiber strands and meshes alone, which can be correlated to the tensile load carried by TRM composite specimens. The tensile testing setup for the TRM composite is shown in Fig. 6. Factors such as the type of fiber used, the strength of the mortar substrate, the volume of fibers added, mesh layers, and the thickness of the mortar matrix determine the composite's tensile strength and performance. The following sections provide some details relating to the tensile testing of NFTRM composites.

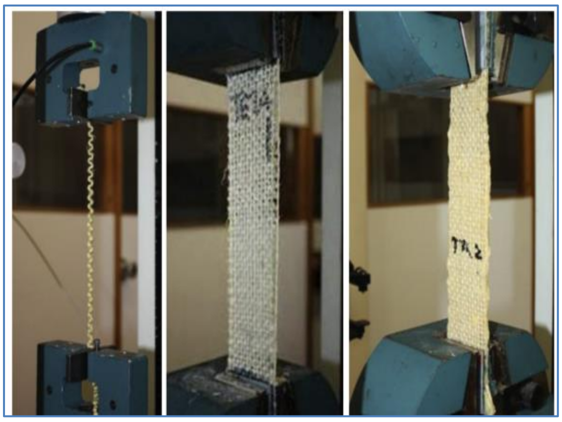

Fig. 5 Tensile tests on single strands and meshes [26]

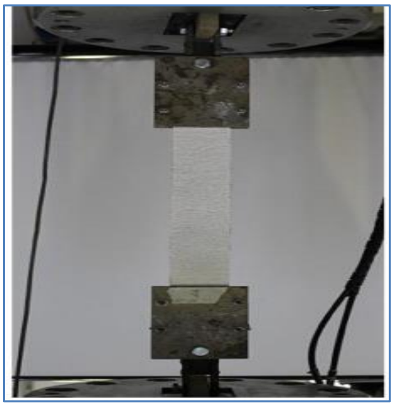

Fig.6 Tensile test on the composite [26]

4.2 Sample coupon shape

Generally, TRM composites are tested for tensile strength using universal testing apparatus. Various coupons are available for casting the TRM specimens, including dog bones, rectangular prismatic, and tabbed coupons, as shown in Fig. 7 [32]. Dog bone coupons are generally preferred to other shapes as the failure area is predictable, i.e., in the central region, since their cross-sections are smaller. As a result, it becomes easier to identify the cause of the failure. Failure may occur anywhere on the rectangular specimen, so observing the entire coupon for signs of failure is important. Including the gripping area, transition zone, and central area, the specimen should have an overall length of 400 mm. Textile fabrics are parallel to the longitudinal specimen axis and symmetrical in width and thickness [33].

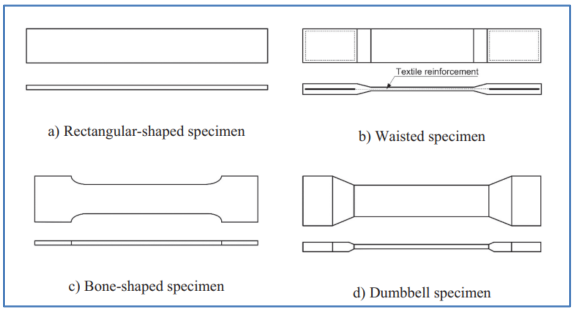

Fig. 7 Shapes of TRM tensile test specimens [32]

4.3 Gripping system

The gripping type is an important factor in stress distribution and failure type in TRM composites. Examples of gripping types are self-tightening, pinching, webbing, rope and thread, hydraulic, wedge, pneumatic, clevis-type, clamping, and plexiglass. Researchers often use common clevis and clamping gripping systems to test the tensile performance of TRMs, as shown in Fig. 8 [33]. When simulating field boundary conditions from a typical installation and obtaining design parameters, a clevis grip (pin action) is used. There is only a transfer of shear stresses. Due to the slippage of the fabric, the fabric's full strength is never reached in this grip type. In order to obtain a complete characterization of the composite, it is necessary to induce a tensile failure of each constituent material using a clamping grip [34]. Using aluminum tabs provides a uniform stress distribution to the coupon [35]. The responses that are shown can be bilinear or trilinear depending upon the gripping system that are used. In the recent times, neoprene rubber sheets are glued to the edges to avoid the crack development during the insertion of the specimen into the gripping system.

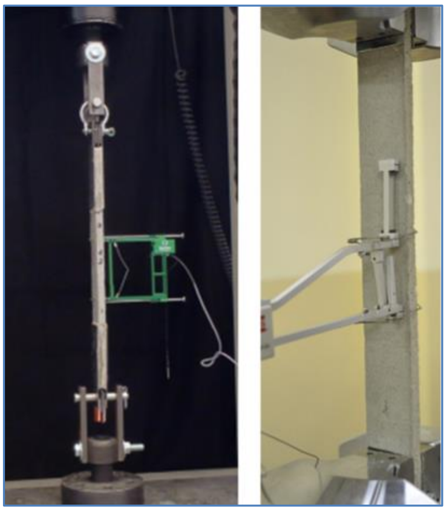

Fig. 8 Clevis and clamping grip [34]

4.4 Apparatus for tensile testing

The tensile testing of TRM composites is conducted using a universal testing machine. A displacement rate of 0.3-0.5 mm/min is generally adopted. Tensile testing is conducted in displacement control mode with a 150-300 mm gauge length. The strain rate is measured with LVDTs and extensometers, the applied load is measured with a load cell to study the crack pattern, and a high-resolution camera is attached for viewing the results [36][32][33].

4.5 Response of TRM to tensile loading

Fig. 9 shows that trilinear behavior. It is observed and identified in three stages. The mortar is uncracked at the beginning, the response is linear until the first crack appears, and the axial stress equals the mortar's tensile strength at the end. This is primarily responsible for the composite's stiffness and load-bearing capacity. Stage two (tensile test method for textile reinforcement) begins with the appearance of the first crack in the mortar. Stage two consists of the gradual development of cracks and the observation of multiple cracks. As a result of large cracks, an uneven response curve is observed, resulting in a load drop. The crack width increases in stage three, but no new cracks are observed. The tensile strength of the TRM composite is determined at this stage. Until the failure, there is a nearly linear branch, where the behavior of the existing composite is primarily influenced by its textile strength and stiffness [3][37][38]. The failure modes observed can be classified into two types. The rupture and slippage of textiles with multiple cracks [12]. Fig. 9 shows three types of stress-strain behavior based on the bond between fabric and mortar. A good bond between fabric and mortar results in trilinear behavior during the elastic, crack development, and failure stages. It is noticed that the stress-strain curve exhibits a bilinear behavior when the bond between the fabric and matrix is insufficient. An uncracked composite is observed in the elastic region in the first stage.

After the first crack, fabric slippage occurs along with pull-out and failure of fabric filaments due to poor bonding between the fabric and matrix [32].

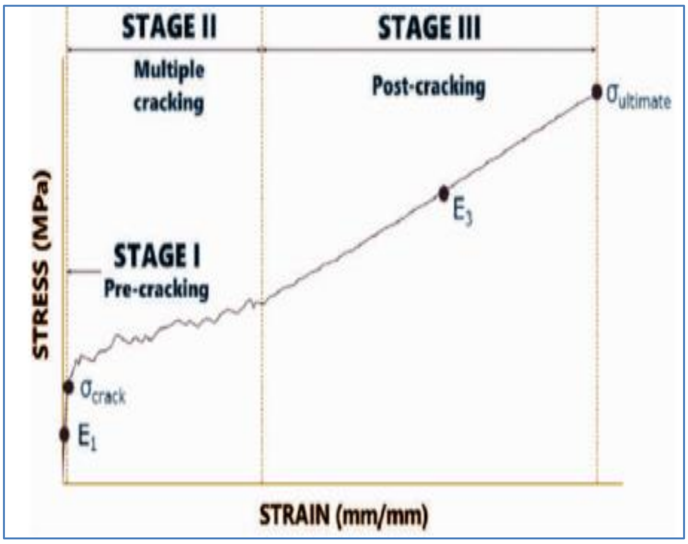

Fig. 9 Tensile behavior of TRM specimens [3]

4.6 Failure of the TRM specimen

Two types of failure modes have been observed. Textile ruptures and slips with multiple cracks. The increase in reinforcement ratio will result in brittle rupture and a sudden loss of bearing capacity. As a result, cracks are also more likely to form [12][38]. Fig. 11 illustrates the possible failure types of the TRM composite. A tensile failure may occur near the gripping, as shown in Fig. 10.Fig. 11 illustrates a failed TRM specimen subjected to tensile loading. It depends on the specimen's shape used for testing to determine the failure plane.

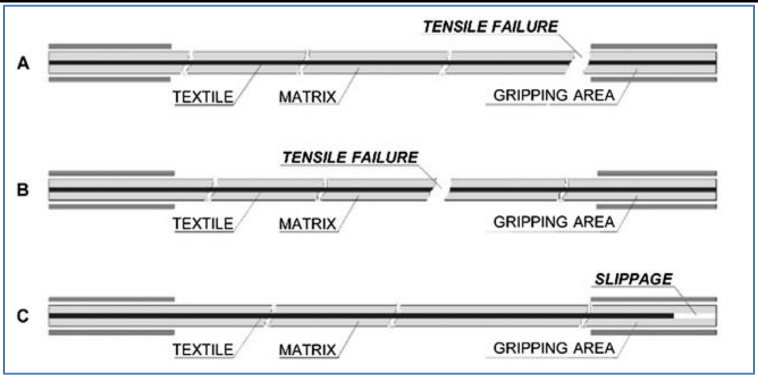

Fig. 10 Failure modes of TRM composite under tensile loading [27][39]

Fig. 11 Tensile test specimen failed after TRM [26]

5. Conclusion

In conclusion, composite materials have a wide range of applications in various fields because of their unique characteristics. The use of synthetic fibers in Fiber Reinforced Polymer (FRP) composites for structural upgrades is not environmentally friendly. The construction industry has therefore adopted natural fiber-reinforced cementitious composites (NFTRCCs) as an environmentally friendly alternative. An NFTRCC consists of a natural fiber mesh embedded in an inorganic cementitious substrate, with the mesh carrying tensile loads and the matrix transferring uniform stress. Natural fiber selection, orientation, thickness, and grid opening size significantly impact the composite's ability to carry tensile loads. As a result of their low cost, lightweight, and environmentally friendly characteristics, natural fibers are becoming increasingly popular in TRM composites. Despite this, natural fibers are susceptible to degradation due to factors such as ultraviolet radiation, dampness, humidity, temperature, and microorganisms. In order to address this issue, fibers can be treated in various ways, including surface, physical, and chemical treatments. A chemical treatment results in a covalent bond between the cellulose surface and the matrix, which enhances the load-carrying capacity, durability, cohesiveness, and bonding properties of the fibers. The optimal treatment may vary depending on the type of fiber and the application. Further study is required to determine the behavior of treated fibers in various cementitious mortars. TRM composites can significantly improve performance and durability when properly treating natural fibers. In order to assess the durability and long-term behavior of natural fiber as well as the bond between structural members and composites, further studies are required.

A review of the performance and behavior of TRM composites incorporating natural reinforcing mesh and structural upgrading studies using TRM has been presented. In summary, the following conclusions can be drawn:

1. For TRM composites to perform well in tensile tests, the fiber type, weaving type, spacing of fabric mesh, specimen geometry, the tensile strength of fiber, strength and durability of mortar matrix, gripping system, number of layers of fabric incorporated, and thickness of mortar must all be taken into account.
2. The chemical treatment of natural fibers used in TRM specimens assists in overcoming the hydrophilic nature of the natural fiber by enhancing the load-bearing capacity and improving the adhesion between the cementitious mortar and fiber mesh, thus enhancing durability and overall performance.
3. In the future, NFTRM composites may be used as the structural upgrading system after they have been treated with the appropriate surface and chemical treatments. In terms of strength, NFTRM is on par with glass fiber TRM.
4. Compared to rigid clamps, which allow slippage because of the lack of friction between the fabric and the mortar substrate, hydraulic grips or bolted clamps prevent slippage of mortar composites.
5. Natural fiber textile reinforced cementitious mortar is becoming increasingly popular in engineering and construction due to its eco-friendliness and ability to contribute to sustainable development. It is possible to use NFTRM in various applications by treating fibers properly and appropriately to enhance their durability and hydrophobic properties.
6. It is necessary to conduct further research on the long-term reliability of NFTRM composites. Furthermore, fatigue performance, bond behavior between fabric and mesh, and developing standard methodologies for NFTRM composites should be considered.

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