A Review on Mechanical Properties of Inorganic–Matrix EBR System

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Abstract: With a large number of important and commemorative historical buildings in the maintenance and reinforcement of the increasingly stringent requirements, the role of inorganic–matrix EBR reinforcement system in the existing masonry structures reinforcement is also increasingly concerned. In this paper, the mechanical properties of textile, mortar and composite materials are compared and analyzed, and the influence of different parameters on the test results is discussed. The results exhibit that the strength range of each material is obvious. For textiles, the tensile strength ranges from 1120 MPa to 5800 MPa, and the elastic modulus ranges from 55.6 GPa to 276.6 GPa. For mortar, the compressive strength is from 12.3 MPa to 80 MPa, and the elastic modulus is from 6 GPa to 39 GPa. In addition, the cracking process of composite specimens can be divided into three stages: un-cracked, crack development and cracked. All kinds of test results can not be compared with the same standard and conditions, due to the significant differences in specimen designs and loading methods, which provides the research direction for the next stage of test and theoretical analysis.

1. Introduction
Externally bonded reinforcement (EBR) system is widely used as a way to retrofitting existing structures, because this system can improve the overall strength without altering the shape and size of the structural members [1]. EBR system can be divided into organic-matrix and inorganic-matrix according to the natural characteristics of the materials used in the surface of the substrate. The main representative of the former is fiber reinforced polymer (FRP), while the latter is typically represented by textile reinforced mortar (TRM), fabric reinforced cementitious matrix (FRCM) and textile reinforced concrete (TRC).

FRP has been used in the repair of various structures due to its high tensile strength, toughness and corrosion resistance [2,3]. However, some shortcomings of FRP have also been found due to the incompatibility of epoxy resin with clay substrate, non operability in low temperature and on uneven surface [4,5]. TRC, a novel EBR system with textile embedded into inorganic matrix, is combined with high-performance fine-grained cement concrete by using alkali resistant glass, carbon fiber or aramid fabric [6]. FRCM, another special type of EBR system, is characterized by dry-fibers in textile form impregnated with a cementitious mortar enriched with short fibers [7]. In addition, EBR system using inorganic matrix appear particularly promising for application to cultural heritage, for which additional specific requirements must be satisfied: (i) respect of authenticity in terms of materials and structural behaviour, (ii) compatibility with original substrates and decorative settings, (iii) reversibility, intended as substitutability and removability, (iv) principle of minimum intervention [8].

Compared with the systematic and consolidated research on the EBR system based on resin-matrix...
(FRP) [9,10], the study on the EBR system based on mortar-matrix is still at an initial stage. Some experiments have been performed in the aspects of mechanical behavior and composite-to-substrate bonding properties [7,11-14]. As an important component of the basic test, the tensile behavior of EBR system has attracted more and more attention due to the general failure of bonding. Moreover, experimental study on the flexural properties of EBR system has also been carried out [15]. All the above studies provides theoretical basis for scholars to further understand the mechanical properties of inorganic–matrix EBR system.

In this paper, the related research results published in recent years were systematically summarized from the aspects of the basic mechanical properties of textiles, mortar matrices and composites, as well as the cracking pattern of composite specimens. On this basis, some problems that can be further studied are put forward.

2. Mechanical properties of materials

2.1. Properties of textiles and mortar matrices

Fig. 1 exhibits the different types of textiles and fibers, which represents material properties of multiple component and type. The geometric dimensions of the commonly used textile materials are shown in Fig. 2, which displays the significant differences in the dimensions of the fabrics used in the reinforcement system in the weft and warp directions.

![Fig. 1. Types of textile and fabric reinforcements: a) – c) [1]; d) – g) [12] and h) – l) [14].](image)
Fig. 2. Geometrical dimensions of textile reinforcements [7].

The mechanical properties of textiles, fibers and mortars are shown in Table 1 and Table 2. It can be seen from the table that although various materials have been tested, the corresponding results (tensile strength and elastic modulus) exhibit significant differences. In addition to the different properties of materials, the change of test setup and clamping methods also have a significant impact on the difference of test results. Moreover, as far as the mortar matrix is concerned, the selected parameters are also significantly different, which makes it impossible to make parallel comparison between different published articles.

Table 1. Material properties of the textile and fiber.

| Textile & Fiber | Description                    | Tensile strength (MPa) | Elastic modulus (GPa) | Cross section area (mm²) |
|-----------------|--------------------------------|------------------------|-----------------------|--------------------------|
| PBO–1 fiber [7] | Roving in the warp direction   | 3900.00                | 215.90                | 0.41                     |
|                 | Roving in the weft direction   | 3430.00                | 276.60                | 0.21                     |
| PBO–2 fiber [7] | Roving                         | 3175.00                | –                     | 0.22                     |
| Glass fiber [7] | Yarn in the warp direction     | 1233.00                | 55.60                 | 0.90                     |
|                 | Yarn in the weft direction     | 1120.00                | 60.50                 | 0.92                     |
| Carbon fiber [7]| Roving                         | 1944.00                | 203.00                | 0.42                     |
| Carbon [14]     | Bi-directional                 | 4900.00                | 240.00                | 0.52                     |
| Basalt [14]     | Bi-directional                 | 3080.00                | 95.00                 | 0.41                     |
| PBO [14]        | Unidirectional                 | 5800.00                | 270.00                | 0.47                     |
| Carbon yarn [14]| Unidirectional                 | 1850.00                | 150.00                | –                       |

2.2. Properties of composite specimens

The geometric dimension and loading rate of the composite specimen are shown in Table 3. Although the thickness of the specimen can be determined as 10 mm, the variation of the total length and width is relatively obvious. In addition, the loading rates of the composite specimens are significantly different, resulting in significant differences in the stress–strain response curves (Fig. 3).

Table 2. Mechanical properties of the mortars.

| Mortar                          | Compressive strength (MPa) | Flexural strength (MPa) | Elastic modulus (GPa) | Unit weight (kg/m³) |
|---------------------------------|-----------------------------|-------------------------|-----------------------|---------------------|
| Mineral [1]                     | 56.30                       | 10.30                   | 22.00                 | –                   |
| Polymer–modified cement [1]     | 22.80                       | 6.90                    | 10.30                 | –                   |
| Cement (4 cords/inch) [1]       | 49.00                       | 5.50                    | 31.50                 | –                   |
| Mineral NHL (4 cords/inch) [1]  | 20.60                       | 5.40                    | 11.40                 | –                   |
| Cement (12 cords/inch) [1]      | 49.00                       | 5.50                    | 31.50                 | –                   |
| Mineral NHL (12 cords/inch) [1] | 20.60                       | 5.40                    | 11.40                 | –                   |
| with PBO fibers [7]             | > 15.00                     | > 2.00                  | > 6.00                | –                   |
| with glass fibers [7]           | 27.13                       | 8.38                    | 8.00                  | –                   |
| with carbon fibers [7]          | > 20.00                     | 3.50                    | > 7.00                | –                   |
| Mortar–15 (15MPa) [13]          | 17.00                       | 3.60                    | 12.50                 | 1650.00             |
| Mortar–30 (30MPa) [13]          | 32.00                       | 7.10                    | 27.50                 | 2194.00             |
| Mortar–45 (45MPa) [13]          | 50.00                       | 6.20                    | 34.50                 | 2275.00             |
Table 3. Geometric dimensions of composite specimens.

| Literature | Total length and cross section | Loading rate |
|------------|--------------------------------|--------------|
| [1]        | 600 mm × 50 mm × 10 mm         | 0.6 mm/min   |
| [7]        | 400 mm × 40 mm × 10 mm         | 0.1 & 0.5 mm/min |
| [12]       | 500 mm × 50 mm × 10 mm         | 1 mm/min     |
| [13]       | 410 mm × 60 mm × 10 mm         | 0.3 mm/min   |
| [14]       | 400 mm × 60 mm × 10 mm         | 0.3 mm/min   |

Fig. 3. Typical stress–strain response curves of composite specimens: a) [11]; b) [16]; c) [17].

2.3. Tensile test: experimental results

The characteristic stress–strain response curve of inorganic-matrix EBR system under tension is displayed in Fig. 4. As in previous studies [18, 19], the response process is mainly divided into three stages: uncracked (I), crack development (II) and cracked (III), and the general trend can be obtained. In the first stage (I), the response is linear and the mortar has a considerable contribution to the bearing capacity and stiffness. Once the stress exceeds the tensile strength of the matrix, crack (II) is captured and a reduction in stiffness can be determined. The first crack usually appears in the middle and near the end of the specimen. There will be subsequent cracks between the existing cracks until the number of cracks is stable. In the final stage (III), the additional applied strain leads to the propagation of existing cracks rather than the development of new cracks, the mortar fragments are discharged, and the specimen is cracked finally.
3. Conclusions
In this paper, the basic mechanical properties of the inorganic-matrix EBR system are comprehensively summarized. It is undeniable that the current research results of the reinforcement system are fruitful. The conclusions and comments are summarized as follows:

1) The strength and elastic modulus of textile and mortar varied widely, and the single mechanical property of each material was perfect, but the strength of composite material could not be fully utilized;

2) More attention was paid to the special parameters and other parameters were ignored in the experiment, which led to the failure of parallel comparison between different experiments;

3) How to match different materials scientifically and reasonably in order to make composites give full play to their comprehensive properties remains to be studied;

4) There are few achievements on the properties of multi-layer textile composites, and more experimental studies should be carried out;

5) In addition, there are significant differences in the design of geometric dimension, loading methods and rates, and a unified regulation should be put forward. Under the same standard, quantitative comparison has more theoretical and practical significance.

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