A R C H I T E C T U R E C I V I L E N G I N E E R I N G E N V I R O N M E N T
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APPLICATION OF NON-METALLIC FABRICS AS REINFORCEMENT IN THIN-WALLED PRECAST CONCRETE MEMBERS

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A b s t r a c t
Textile Reinforced Concrete (TRC) is an innovative building material especially suited for lightweight precast members such as shells, road-screens and façade elements. In such elements very often durability is more important than load capacity. Due to resistance to corrosion it can be used with a thickness in the range of 10 to 40 mm, which cannot be achieved with standard steel reinforcement. Furthermore, due to its exceptionally low weight-to-strength ratio, it leads to structural solutions that are both sustainable and economically attractive. Strong fabrics available today are manufactured from glass, carbon or PVA (poly-vinyl-alcohol) fibres. Contrary to steel reinforcement, such fibres in the textile can be positioned in almost any direction and subsequently can be nearly perfectly adopted to the orientation of the applied load. Therefore, it is possible to create an extremely effective reinforcement. On the other hand, the stress-strain relations are quite different in steel (with yielding) and in textiles (fully linear). This influences significantly the behaviour under loading. The concept of Textile Reinforced Concrete (TRC) with fabrics made of alkali-resistant glass is a scope of the recent decade research activity, especially in two cooperating research centres in Germany, Dresden and Aachen. Taking advantage of the experience gained by German experts, now this new concept is being developed in the Silesian University of Technology, Gliwice, Poland. The paper presents a series of tests of thin plates 1.20×1.00 m, 40 mm thick, made of self-compacting concrete and reinforced with orthogonal fabrics made of alkali-resistant glass (AR-glass), poly-vinyl-alcohol (PVA) and carbon fibres. Some reference elements in tests were reinforced with steel wires. Such members were tested in relation to bending capacity. Some results of accompanying tests are presented too, e.g. on anchorage length of different textiles.

S t r e s z c z e n i e
Beton zbrojony tekstyliami (TEKSBET) jest nowym materiałem budowlanym znajdującym zastosowanie do lekkich elementów prefabrykowanych, takich jak: przekrycia powłokowe, drogowe ekrany akustyczne i płyty elewacyjne. W tego typu elementach bardzo często wymogowi trwałości stawia się większe wymagania od warunku nośności. Ze względu na wysoką odporność korozyjną, grubość elementów może zostać ograniczona od 10 do 40 mm, co jest nieosiągalne przy stosowaniu tradycyjnego zbrojenia ze stali. Ponadto, ze względu na nadzwyczaj niski stosunek ciężaru własnego do nośności, otrzymuje się rozwiązanie, które nie tylko wpisuje się znakomicie w ideę zrównoważonego rozwoju, ale też jest korzystne z punktu ekonomicznego. Wytrzymałe siatki do zbrojenia betonu, które dostępne są obecnie na rynku, wykonywane są z włókien szklanych, odpornych na alkalia, włókien węglowych oraz z PVA (Poli-winyl-alkoholu). W odróżnieniu od zbrojenia ze stali, siatki tekstylne mogą być usytuowane w niemal dowolnym kierunku, co skutkuje lepszym dopasowaniem zbrojenia do rozkładu sił w przekroju. W ten sposób można uzyskać niezwykle skuteczne zbrojenie. Z drugiej strony, zależności „σ-ε" są zupełnie odmienne w stali (z półką plastyczności) i w zbrojeniu tekstylnym (zależność liniowa w pełnym zakresie pracy). Ta właściwość wywiera znaczący wpływ na pracę pod obciążeniem. Idea Betonu Zbrojonego Tekstyliami (ang. Textile Reinforced Concrete – TRC) w postaci siatek wykonanych z włókien szklanych odpornych na alkalia stała się, w przeciągu ostatniej dekady, przedmiotem badań naukowych, prowadzonych przede wszystkim przez dwa ośrodki naukowe w Niemczech, w Dreźnie i w Aachen. Z wykorzystaniem doświadczeń tych ośrodków, to rozwiązanie jest przedmiotem badań prowadzonych na Politechnice Śląskiej w Gliwicach. W artykule przedstawiono badania cienkich płyt o wymiarach 1.20×1.00 m i grubości 40 mm, wykonanych z betonu samozagęszczalnego i zbrojonego siatkami ortogonalnymi wykonanymi z włókien szklanych odpornych na alkalia, z PVA oraz z włókien węglowych. Płyty porównawcze były zbrojone siatkami stalowymi. Elementy były badane pod kątem nośności na zginanie. Podano również niektóre wyniki badań towarzyszących, takich jak badanie przyczepności siatek tekstylnych różnego typu do betonu.

K e y w o r d s: **Textile reinforced concrete; Thin-walled prefabricates; Alkali resistant glass; Poly-vinyl-alcohol; Carbon fibres; Self-compacting concrete.**

1. INTRODUCTION

The concept of alternative reinforcement towards traditional steel wires/bars for concrete structures, in form of textile reinforcement was introduced in the 1990s in Germany. Textile reinforced concrete (TRC) is a composite building material which comprises of fine-grained high quality concrete matrix and non-metallic, alkali-resistant reinforcement. Since the idea of reinforcing concrete members with traditional steel bars is based on good bond between both materials, it requires adequate concrete cover whose value depends on the three basic demands: (1) safe transmission of bond forces, (2) protection of the corrosion endangered steel (ensuring both the chemical and physical concrete protection), (3) an adequate fire resistance. In design, in accordance with the rules given in EN 1992-1-1 (Eurocode 2: Design of concrete structures. Part 1-1), at least 15 mm (or the rebar diameter) concrete cover for reinforcement is required, for 50 years of intended working life in the less corrosive environment – dry or permanently wet. This rule does not refer to textile reinforced concrete, in which, due to the corrosive resistant nature of non-metallic fibre materials (e.g. alkali-resistant glass, carbon, and others), the concrete cover is no longer needed as chemical protection. High corrosion resistance of non-metallic fibres and low self-weight of textile fabrics allow to produce lightweight, thin-walled elements [1]. Additional benefit from application of textile fabrics as reinforcement, particularly those multidirectional, is the possibility to align the yarns in the direction of expected tensile stresses, leading to an increase in their effectiveness and load-carrying capacity.

This concept became a subject of worldwide research activities, as a scope of experimental works and numerical analyses with the use of sophisticated mathematical solutions. The first applications in real structures prove the high utility potential of this modern, high-tech building material. The fundamental approach towards textile reinforced concrete structures had been prepared under auspices of RILEM Committee (TC 201-TRC) in cooperation with ACI-Committee 549 „Thin Reinforced Cementitious Products and Ferrocement" within the period of 2002÷2006. The state-of-the-art report No. 36 of RILEM TC 201-TRC was published in 2006 by scientific staff of two collaborative research centres, i.e. Aachen University (W. Brameshuber, *et al.*) and Dresden University of Technology (M. Curbach, *et al.*) [2]. Taking advantage of the experience gained by German experts, now this new concept is being scientifically researched also in the Structural Engineering Department of the Silesian University of Technology, Gliwice, Poland.

This paper presents the test results of textile reinforced concrete plates subjected to bending. The comparison to traditionally steel-reinforced concrete elements is shown. Some results of accompanying tests are presented too.

Furthermore, brief specification is given of textiles which are in use in concrete elements and some practical applications are listed.

2. GENERAL CLASSIFICATION OF TEXTILE FABRICS

The comprehensive review of all kinds of textiles which are recently accessible on market was given by Bobeth [3]. Afterwards, the choice of these textiles which could be used as a reinforcement for cement based composite materials was presented by Curbach [4].

Non-metallic fabrics for reinforcing concrete elements can be classified as:

- due to the material of fibres:
- glass fibres – only as alkali resistant glass fibres, when used as a reinforcement of cement based materials, due to making fibre-concrete contact area durable,
- asbestos fibres – besides their very good mechanical properties and low price, in Poland withdrawn from market in 1997, due to its cancer-invoke threat,
- poly-vinyl-alcohol (PVA) fibres – PVA, produced from artificial polymers, non-corroded and high resistant to concrete alkali environment,
- polyacrylonitryl (PAN) fibres – currently unused, although the most popular carbon fibres are derived from PAN,
- carbon fibres – the most popular and extensively used in civil engineering applications due to high tensile strength, low weight, low thermal expansion, high fire- and alkali-resistance,
- polypropylene (PP) fibres – unused as a reinforcing due to their low Young's modulus value,
- aramid fibres – characterized by high tensile strength and high Young's modulus, however, moisture sensitive thereby rarely in use as reinforcement,
- polyethylene (PE) fibres – unused as reinforcement due to their very low Young's modulus value,

- high density polyethylene (HDPE) fibres – having higher tensile strength and being harder than low-density polyethylene can be used as a reinforcement,
- hybrid fabrics – comprising different kinds of textiles, adjusted to direction and value of stresses, e.g. fabrics combine lower cost, glass yarns with more expensive, carbon yarns.

• due to the shape:

- flat fabrics – made from individual yarns or bundles,
- three-dimensional fabrics.

• due to connections between yarns:

- knitted fabrics – less efficient due to possibility of deconsolidation,
- knitted fabrics assembled together by means of ties,
- knitted fabrics coated with epoxy or other resin.

For further classification see Offermann *et al.* [5].

3. PRACTICAL APPLICATIONS

Nowadays, it is possible to find already several successful applications of textile reinforced concrete in real structures. The perfect example creates the footbridge at opening of horticultural show in Oschatz 2006 - designed, tested and finally accomplished by the TU Dresden team under supervision of M. Curbach. The full scale structure sizes 2.5 m in width × 8.6 m in span. The structure has been assembled from 10 equal, 0.9 m long and only 3 cm thick "U"-shaped units reinforced with textiles and joined together by means of six steel high-diameter bars, without pretensioning [Fig. 1a, d]. The final self-weight of the bridge with total mass of 5 tons is 5 times less in comparison to similar RC-bridge. For better understanding of structural behavior, the full scale tests were carried out on exactly the same structure in Otto-Mohr laboratory of TU Dresden which

Figure 1.
Practical applications of TRC: a) footbridge in Oschatz, Saxony, Germany (2005), b) footbridge in Kempten, Allgäu, Germany (2007), c) strengthening of a hyper shell structure, FH Schweinfurt, Germany (2006) [online resources], d) segmental bridge prototype in front of TU Dresden, Germany

proved satisfactory load-carrying capacity of the structure – the bearing capacity 3 times exceeded design values according to the German Codes. In 2006 the structure was awarded in fib competition for Outstanding Concrete Structures [6]. Having this experience, the next footbridge was erected in Kempten. This bridge is almost twice as long as the first one and reached the span of 15.95 m [Fig. 1b]. The structure comprises of 18 units, each of 0.93 m in length. The self-weight of the bridge is again very challenging and the full mass was only 12.5 tons.

Regardless of achieving the final goals, the designers are aware that for this new material and its practical applications still more research is needed.

Apart from new applications, there is also extensive research on strengthening methods with the use of textile reinforced concrete layers. The very first use of this new method of repairing was executed in 2006 for rehabilitation and retrofitting of the shell structure of Fachhochschule in Schweinfurt [Fig. 1c]. According to designer's data, the strengthening layer was very thin, only 15 mm, and consisted of fine grained concrete and three layers of carbon fabric which was applied layer by layer on the sandblasted rough concrete surface.

Other practical applications include: thin-walled and light-weight ventilated façade systems, structural sandwich panels for façades of industrial buildings, diamond-shaped lattice frameworks or road-screens. Implementation of TRC sandwich panels for modular buildings is in design study phase. Also use on curved surfaces, e.g. the barrel shells is being considered [2].

High potential of TRC is not only limited to strictly civil engineering applications. Also other branches take advantage of this new concept. There are known examples of valuable works of TU Dresden students. They designed and self-made not only the lightest canoes, but also the other concrete boats - exceptional "Drehsden" watercraft ("dreh" is German "rotate") and unusual "Gelber Oktober" submarine [Fig. 2] [10].

Textile reinforced concrete is proper structural material whenever the requirements for light-weight and filigree structures shall be fulfilled.

4. EXPERIMENTAL INVESTIGATIONS

4.1. Scope of research

Since the diameter of the fibres in the textile reinforcement is lower than the necessary diameter of steel reinforcement and there is no minimum concrete cover requirement, the casting of very thin concrete members is possible. In such a case – neglecting the fire resistance – the thickness of structural members depends only on the necessary cover to ensure a proper anchorage of the reinforcement and to avoid splitting failure.

The general aims of the tests were the following:

- Comparison of load-bearing behaviour of three different kinds of textiles (alkali-resistance glass yarns, poly-vinyl-alcohol with PVC coating and hybrid: carbon with alkali-resistant glass yarns) as reinforcement of the thin, only 40 mm thick concrete plates.
- Selection of concrete matrix made of different concrete mixes suitable for precise manufacturing of thin elements.
- Further recognition of load-bearing behaviour of textile reinforced concrete with comparison to

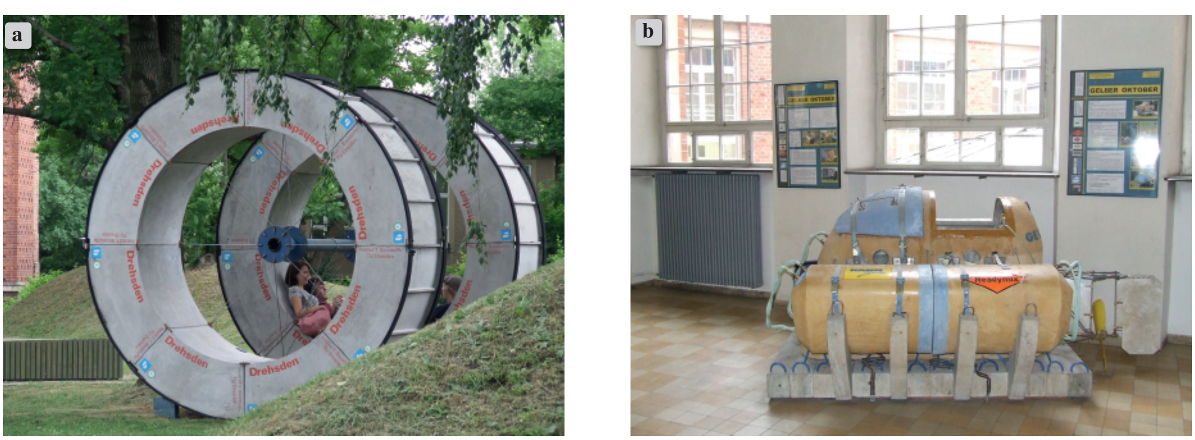


Figure 2.
Other applications of TRC, students' works: a) "Drehsden" watercraft, TU Dresden, Germany, b) "Gelber Oktober" unusual submarine, TU Dresden, Germany

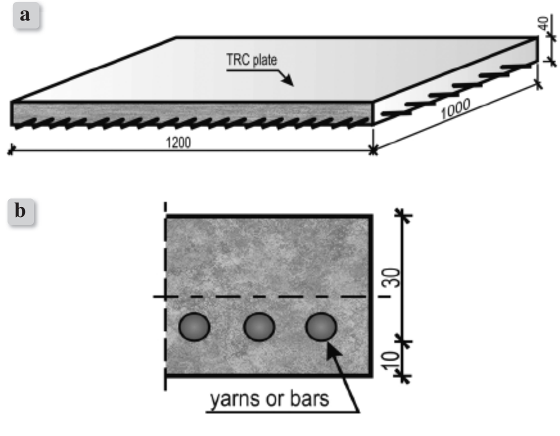


Figure 3.
Textile reinforced plate geometry: a) axonometric view, b) cross-section

conventional, steel reinforced concrete.

• Investigation on behaviour of the textile reinforcement anchored in the specific concrete matrix (fine-grained self-compacting concrete).

4.2 Description of elements

The flexural behaviour has been examined on twelve concrete plates, with dimensions 1200×1000 mm in plane and only 40 mm in depth (Fig. 3).

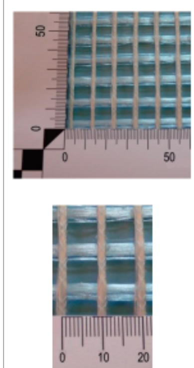
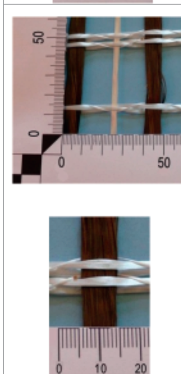
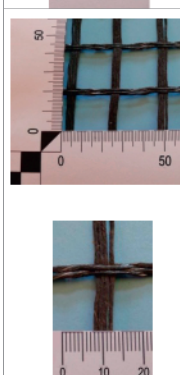
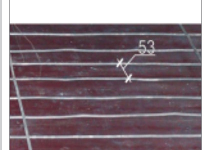
In research programme the plates were divided due to the kind and the type of reinforcement into four groups of three elements each.

The elements were reinforced with flat, orthogonal fabrics, cast with ensuring the minimal concrete cover of 10 mm (no durability requirement). The following kinds of textile fabrics were considered: alkali-resistant glass (Series-02), poly-vinyl-alcohol with PVC coating (Series-03) and hybrid – made of carbon yarns in warp direction and AR-glass yarns in weft direction (Series-04). For comparative tests (Series-01) the conventional fabrics made of Ø4.0 mm plain steel wires were chosen. Detailed specifications for applied fabrics are given in Table 1.

The technological task that had to be resolved before casting elements was to ensure the accuracy of small, only 10 mm thick concrete cover. Two solutions were used for this purpose: in reference elements reinforcement was stabilized in formwork, whereas in textile reinforced plates fabrics were primarily stretched with low force of about 0.5 kN/m and released immediately after casting (Fig. 4).

Limitations for concrete mixtures were connected

Table 1.
Properties and geometry of fabrics details (in mm)

Detailed fabric view	Features
1	2
	AR-glass: – type: NWM3-002-05p, – 1600 filaments per yarn, no coating – tensile strength: 56.8 kN/m, – modulus of elasticity: 74.96 GPa, – linear relation σ-ε
	Hybrid (carbon with AR-glass): – geogrid resembling S&P Carbophalt G, no coating, – carbon yarns in the warp direction, – tensile strength in the warp direction: 49.5 kN/m, – carbon yarns modulus of elasticity: 235 GPa, – knitted fabric, – linear relation σ-ε
	PVA with PVC coating: – ARMATEX®M geogrid PVA, with coating, – tensile strength in both directions: 55.0 kN/m, – modulus of elasticity: 58 GPa, – linear relation σ-ε
	Reference steel fabrics: – characteristic tensile strength: 320.0 MPa, – yield strength: 240.0 MPa, – plain wires Ø 4.0 mm at 53 mm, – tensile strength: 57.3kN/m, – modulus of elasticity: 200 GPa

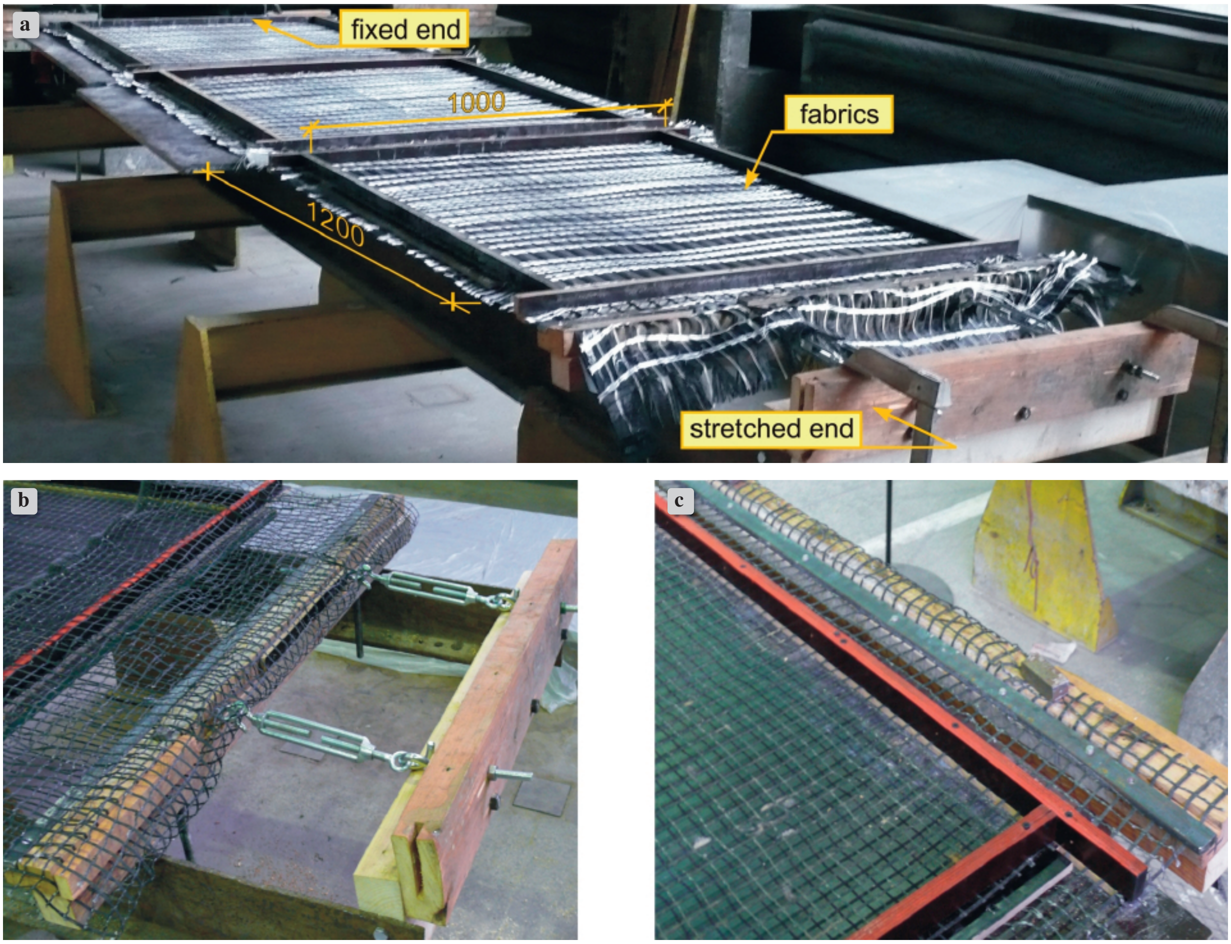


Figure 4.
Formwork with reinforcement made of non-metallic fabrics: a) general view, b) stretched end, c) fixed end

Table 2.
Concrete strength and composition of concrete mixtures [kg/m^3]

Mixture	Cement	Fly ash	Silica fume	Sand	Gravel	Water	SP /VS(*)	w/c ratio	Mean compressive strength $f_{cm,\,cyl}$ [MPa]
				0÷1 [mm]	2÷4 [mm]				
1	2	3	4	5	6	7	8	9	10
TU Dresden	942.0	628.0	50.2	263.8	-	313.7	12.2 / 0	0.35	77.3 (**)
SCC	CEM I 42.5R; 485.0	-	-	859.8	771.9	227.9	4.8 / 1.1	0.47	46.3

(*) *SP* – superplasticizer, *VS* – viscosity stabilizer, (**) $f_{cm,cube}$

particularly with proper concrete infiltration of the fabrics with small mesh. After several trials of mixture components and consistency the one presented in Table 2 was selected.

In fact, it was self-compacting fine-grained concrete. Compared with the high-strength mortar used by German researchers in TU Aachen or TU Dresden (1998), the selected matrix was closer to the ordinary self-compacting concrete (SCC), with reasonable amount of cement.

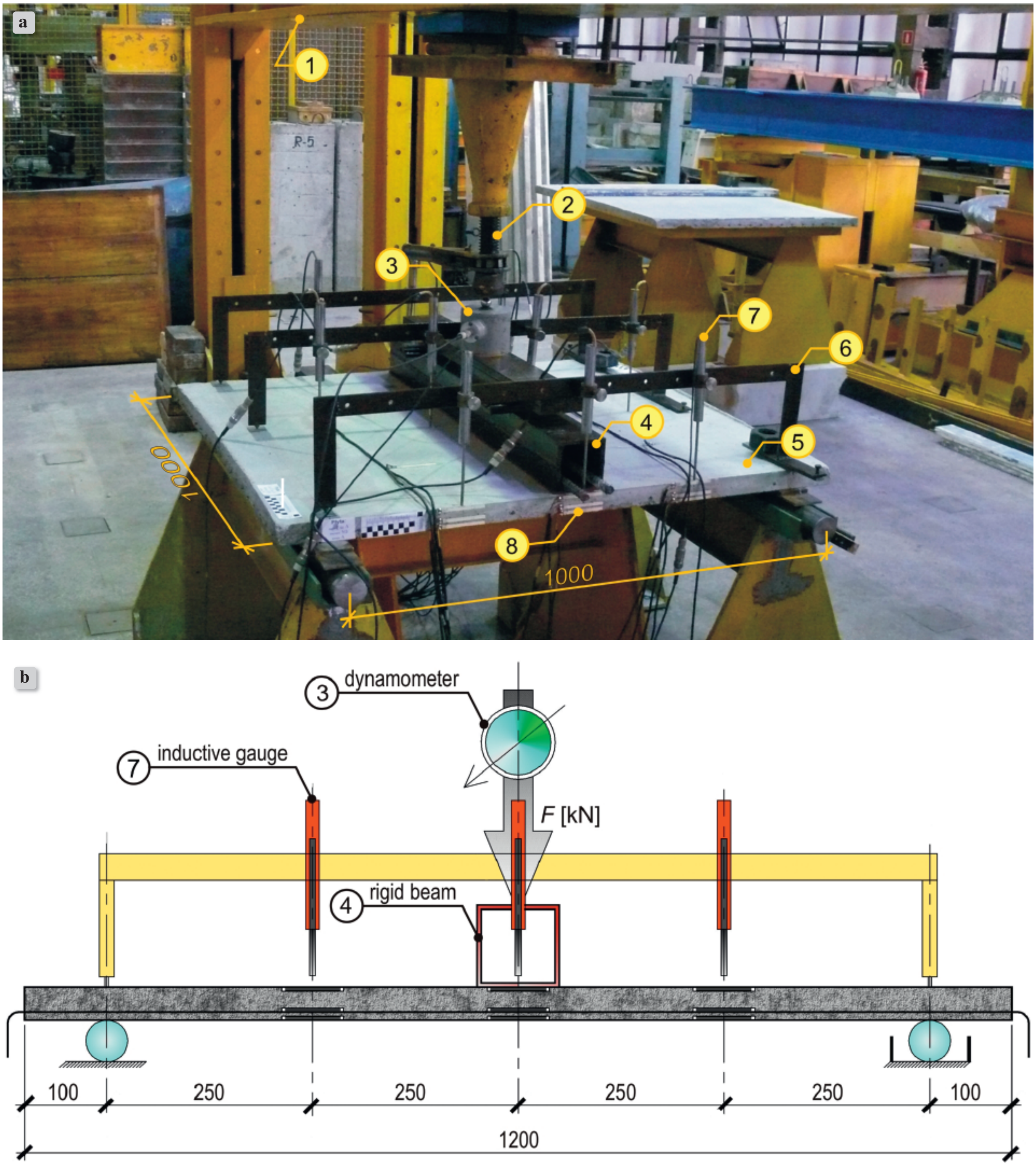


Figure 5.
Testing equipment: a) laboratory test – stand with measuring devices (description in text), b) side view

4.3. Accompanying tests

For general information about anchorage of applied types of textile reinforcement in concrete matrix, accompanying tests were performed.

For the first anchorage length tests the strips of fabric 100 mm wide were chosen and tested with an effective length of 500 mm. They were embedded in concrete base of 300×300 mm in plane and with either 50, 100 or 150 mm embedment length. The test results were following:

- For the smallest embedded length of 50 mm the slip of all fabrics was observed under similar average force of about 1.8 kN, so the anchorage length was insufficient in this case.
- For the embedded length of 100 mm, still unsatisfactory results were obtained

- the slip of all fabrics was noticed.

- For the embedded length of 150 mm, all fabrics broke at the forces from 4.8 kN to 5,4 kN, and no slip was recorded.

Therefore, it seems that the minimum required anchorage length for a single layer of the fabrics

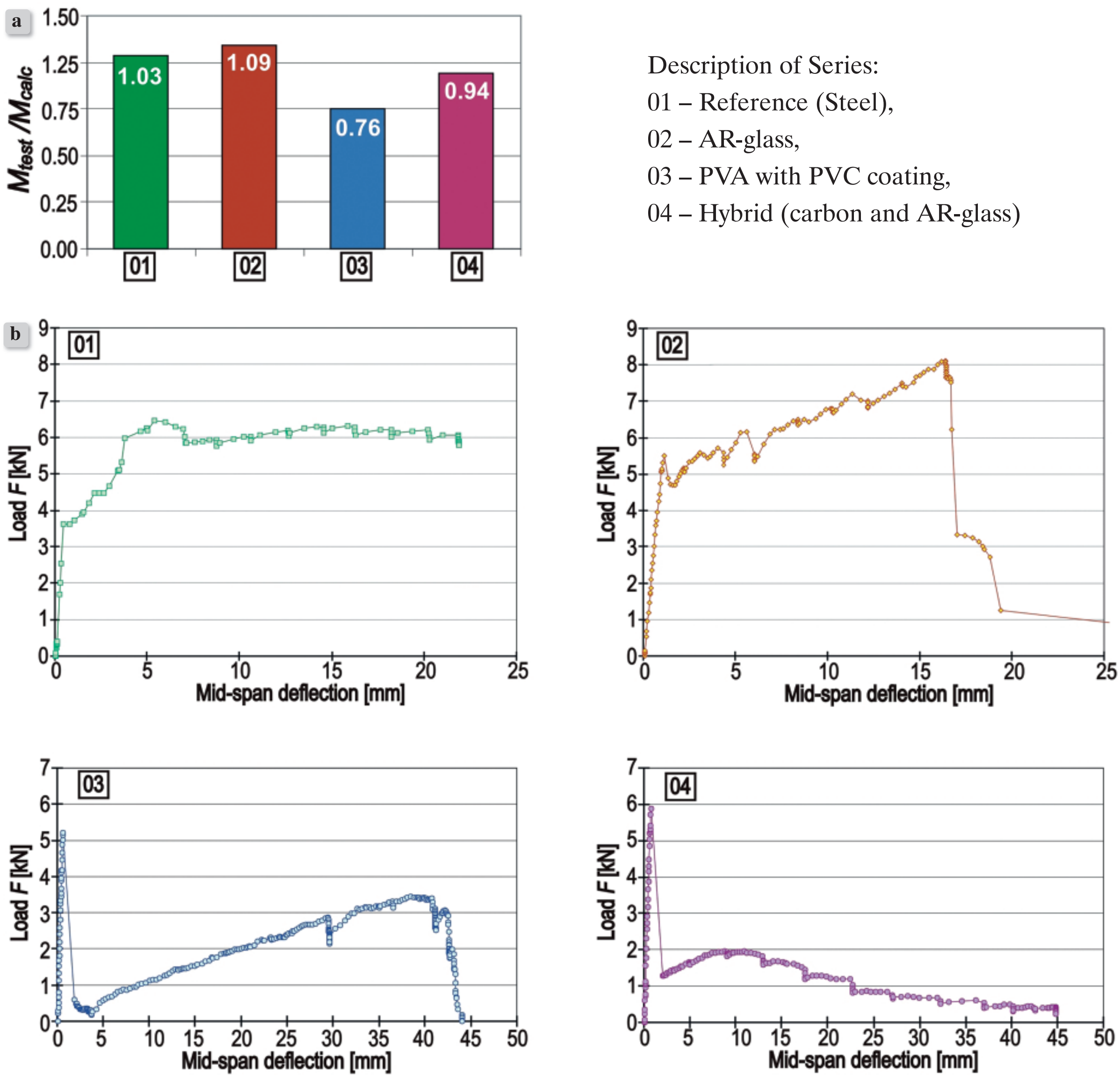


Figure 6.
Basic test results: a) ultimate bending moments from tests compared with calculated values (M_{test}/M_{calc}), b) relationship displacement vs. load (representative diagrams for each of the test series)

taken into account must be at least 150 mm.

Nevertheless, it must be emphasized that these tests were performed only for general recognition of anchorage properties of the fabrics specified for the tests, where two types of them originated from commercial geotextiles. It was sufficient for the simple elements in the tests, but further tests upon understanding of bond properties are planned for more complex prefabricates.

The mean results of tests on strength and modulus of elasticity for particular fabrics were presented in Table 1. Data for steel wires were taken from producer's specification.

4.4. Tests of plates

The elements were tested as simply supported along two edges, in three-point load scheme with concentrated force linearly distributed at mid-span. The stand for the tests is presented in Fig. 5.

The load was induced to element through rigid steel frame „1" by handy hydraulic jack „2" with nominal capacity of 20 kN and was uniformly, linearly transferred to plate „5" by rigid steel beam „4". Load value was measured with dynamometer „3".

The value of applied force F and the related values, such as: concrete strains and plate deflection were measured on both sides of the elements.

Ten inductive gauges "7", symmetrically stabilized along the sides with the use of steel frames "6", were used for measurement. Concrete strains were measured at side edges of plates with the use of 22 electro-resistance strain gauges.

Elements were subjected to static, instantaneous load up to failure. For collecting more precise data, measurement in time intervals of 0.5 sec., instead of controlling force value, was provided for the tests. Primarily, test stand calibration was done at low force level of 0.53 kN. Subsequent loading steps were induced by hydraulic jack rod displacement.

5. EXPERIMENTAL RESULTS

At first, all the plates performed linear behaviour before cracking. Afterwards, in post-cracking phase, the differences between elements appeared (Fig. 6).

Load-carrying capacities of the plates differed in accordance with reinforcing material, due to distinctions in fabrics tensile strengths (see Table 1). Therefore, for proper recognition of particular material usability, the relations between ultimate bending moments from tests and calculated values (Mtest/Mcalc) were compared. These data (see Fig. 6a) proved high quality of AR-Glass and Carbon fibres (Series-02 and -04) as reinforcement. Slightly lower compatibilities between the tests results and theoretical calculations were observed for PVA reinforced plates (Series-03). For Series-03 and -04 sudden drop in load-carrying capacity was observed after cracking (last two plots in Fig. 6b). Afterwards, the plates performed large deflections at failure.

This post-cracking behaviour of the plates is important when taking into consideration specific structural elements (e.g. road-screens), but for most practical applications the first peaks of diagrams are important, according to those presented in Fig. 6b.

6. CONCLUSIONS

The results of the tests of textile reinforced concrete plates have been presented shortly. As it is still new building material, at the beginning, collecting empirical data is very important. The basic aim of the tests concerned explanation of structural behaviour of very thin concrete plates subjected to bending. The behaviour of three different textile fabrics as reinforcement has been discussed on the basis of relationship between linearly distributed static load and deflection. The test results proved the former German observations as to good bond properties between textiles and concrete. In particular, the textile reinforcement made of Carbon fibres showed high potential for structural applications. For the other two geogrids (PVA and AR-glass), their tensile strength was not fully achieved. This behaviour was partly due to complex microstructure of reinforcing textiles that, contrary to conventional steel reinforcement, consist of hundreds of continuous fibres or filaments from which only the outer ones (sleeve filaments) are fully embedded into the cement matrix, whereas central filaments of a yarn (core filaments) remain partially unconnected.

Also, lack of the fabrics impregnation, e.g. with epoxy resin, significantly influenced both the bond properties and ultimate strength.

For typical applications of thin-walled precast TRC members the behaviour up to the cracking is particularly important. From this point of view the initial part of diagrams showed that all kinds of non-metallic reinforcement are useful (Fig. 6b).

On the other hand, considering the final failure phase (like in road-screens) the post-cracking behaviour is significantly different for the elements with various fabrics used in the tests. The usability of the elements with particular fabrics should be considered individually, according to particular requirements.

The elements reinforced with AR-glass fabrics were relatively similar to those reinforced with steel – the load-capacity and the stiffness are comparable.

Significantly different is behaviour of elements reinforced with carbon and PVA fabrics. The initial pre-cracking behaviour was similar to other elements, but the post-cracking load vs. deflection relations were quite different. These elements presented softening and behaved as much more ductile, with deflections two times greater at failure.

Further laboratory tests are currently in progress. The specimens are also subjected to long-term durability tests, mainly at corrosive exposure to chlorides.

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