Journal of Engineering Sciences
and Information Technology
Volume (6), Issue (3) : 30 Jun 2022
P: 124 - 147

ISSN: 2522-3321

مجلة العلوم الهندسية
وتكنولوجيا المعلومات
المجلد (6)، العدد (3) : 30 يونيو 2022م
ص: 124 - 147

Characteristics of carbon reinforced concrete Single-sided short time textile pull-out (SPO) Experiments

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Abstract: Carbon reinforced concrete (CRC) is an innovative alternative to steel reinforced concrete. More and more buildings are being constructed or renewed and strengthened with CRC. Carbon reinforced concrete development is associated with long-term growth in many industries. In addition to the construction industry, the chemical, mechanical engineering and textile industries in particular benefit from the widespread impact.

When carbon reinforced concrete is used in the field of repair and strengthening, it increases the bearing elements' capacities without notable increasing the element's thickness, therefore it does not lead to an increase in the weight of the structure, nor to a change in its original size or shape.

The increasing use of carbon reinforced concrete mainly requires knowledge of its constituent materials' properties in addition to the behavior of the composite, especially under tensile stress, including the bond between fibres and concrete. Detailed knowledge is particularly required in low concrete age is required if the element strengthened with CRC is to be loaded again as soon as possible. The data available on this is still comparatively incomplete. So, it is often necessary to rely on experiment to determine these properties.

Within the framework of this research, tests were performed on carbon concrete with ages of four, five, seven and ten days to determine the bond properties of CRC under tensile stress. The test results were then evaluated and interpreted, then we finally present the resultant material properties of textile concrete used at a young age.

As expected, the force corresponding to the slip value of 1.5 mm increases with increasing age of the sample and is expected to reach the value 5552 N at the age of 28 days. In addition, with the increase in the sample age, the value of the spacing between cracks decreases and the value of the coherence field length decreases as well. In this case, the behavior of carbon-reinforced concrete is similar to that of steel-reinforced concrete.

Keywords: Carbon reinforced concrete (CRC), textile reinforced concrete (TRC), carbon textile reinforcement, material properties, tensile strength, bond mechanisms, SPO.

خصائص الخرسانة المسلحة بنسيج الكربون تجارب شد مبكرة ذات اتجاه واحد لخرسانة النسيج الكربوني (SPO)

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المستخلص: الخرسانة المسلحة بالكربون (CRC)، هي بديل مبتكر للخرسانة المسلحة بالفولاذ. حيث يتم بناء المزيد والمزيد من المباني من الخرسانة الكربونية أو تجديدها وتقويتها باستخدام الخرسانة الكربونية. يرتبط تطوير الخرسانة المسلحة بالكربون بنمو العديد من

الصناعات. فبالإضافة إلى صناعة البناء، تستفيد الصناعات الكيميائية والهندسة الميكانيكية وصناعات النسيج على وجه الخصوص من التطوير الواسع النطاق.

عند استخدام الخرسانة المسلحة بالكربون في مجال الإصلاح والتدعيم، فأنها تزيد كفاءة وقدرة تحمل العناصر الحاملة، دون أي زيادة ملحوظة في سمك العناصر بحيث لا يترتب على ذلك زيادة في وزن المنشأ، ولا إلى تغيير في الحجم والمظهر الحقيقي للمبنى.

يتطلب الاستخدام المتزايد للخرسانة الكربونية بشكل أساسي معرفة خواص المواد المكونة له، خاصة السلوك تحت جهود الشد، بما في ذلك خاصة التماسك بين نسيج التسليح والخرسانة. المعرفة التفصيلية مطلوبة على وجه الخصوص في العمر المبكر لطبقة التقوية من الخرسانة الكربونية، عندما يكون من الضروري إعادة تطبيق الأحمال على العنصر المدعم في أسرع وقت ممكن. نظرًا لقلة المعلومات المتوفرة عن خصائص الخرسانة الكربونية المستخدمة في التقوية حالياً، فمن الضروري غالبًا الاعتماد على التجربة لتحديد هذه الخصائص.

في إطار هذا البحث، تم إجراء اختبارات على الخرسانة المسلحة بالنسيج الكربوني بعمر أربعة، خمسة، سبعة وعشرة أيام لتحديد خصائص التماسك مواد الخرسانة المسلحة بالكربون تحت إجهاد الشد. تم تقييم نتائج الاختبار وتفسيرها وتم عرض خصائص المواد للخرسانة النسيجية في سن مبكرة.

كما هو متوقع، تزداد القوة المقابلة لقيمة الانزلاق البالغة 1,5 mm مع زيادة عمر العينة ومن المتوقع أن تصل إلى القيمة 5552 N عند عمر 28 يوماً. بالإضافة إلى ذلك، مع زيادة عمر العينة، تقل قيمة التباعد بين الشقوق وتقل قيمة طول مجال التماسك أيضاً. في هذه الحالة، نلاحظ تشابه سلوك الخرسانة المسلحة بالكربون مع سلوك الخرسانة المسلحة بالفولاذ.

الكلمات المفتاحية: الخرسانة المسلحة بالكربون (CRC)، الخرسانة المسلحة بالنسيج الكربوني (TRC)، تسليح النسيج الكربوني، خواص المواد، جهود لشد، آليات التماسك، (SPO).

1. General

Carbon reinforced concrete (CRC) is a composite material made of high-performance concrete and reinforcement made of endless carbon fibres. The concrete, also called concrete matrix, consists of sand, cement, water and other substances. The carbon reinforcement is available in rod and mat shapes. The carbon rods are usually produced in a pultrusion process with round cross-sections and different diameters. The mesh reinforcement is manufactured in a textile process, so that it is often called textile. At the beginning of research and development, grid-like reinforcements with comparatively small yarn diameters were used, which is why the term "textile reinforced concrete" (TRC) was introduced. Here, the reinforcements can be made of different fibre materials such as AR glass, carbon or basalt. Carbon reinforced concrete is concrete that has been armed with grids or bars based on carbon fibres. As further literature on the topic of TRC/CRC [1], [2], [3], [4], [5] is recommended.

Textile reinforced concrete is currently gaining a major role in use in construction. It is used either in new buildings or in the repair and strengthening of the old buildings, whereby it can be manufactured using casting and lamination processes. In refurbishment, layer thicknesses of 2 cm can be achieved using TRC or CRC, where 7–8 cm would be necessary with steel reinforced concrete. In addition, the renovation with carbon reinforced concrete can be carried out much faster than conventional renovation with steel reinforced concrete. More and more buildings are being built from CRC [6], [7] and renovated with carbon reinforced concrete, so in-depth knowledge about the material is necessary. This includes the basic knowledge of the corresponding material parameters, especially the behavior under tensile stress including the bond mechanisms between fibre reinforcement and cementitious matrix, and especially at a young age of the strengthening CRC layer, when the reintroduction of the loads on the supporting element is necessary as soon as possible. Since concrete design parameters are currently only available for a few reinforcement materials, it is often necessary to rely on their experimental determination. Therefore, for the further development of the Materials in recent years also modified the test methods repeatedly.

In numerous research projects e.g. by TU Dresden [8], [9], [10], [11], [12], RWTH Aachen University [13] and MFPA Leipzig [14] (all located in Germany), test recommendations for determining the material parameters under tensile loading of TRC resp. CRC were developed. In the following, the tests for quality assurance of the textile concrete are presented and the results interpreted.

2. Research problem and purpose

Many existing structures require maintenance and strengthening. There is currently a modern material called carbon reinforced concrete, where research and numerous practical applications have proven the feasibility of strengthening structures [15], [16], [17], [18], [19]. However, one of the most important difficulties facing engineers and workers in this field is the lack of the necessary design codes and sometimes even the lack of information available on the properties of new developed carbon reinforcements and of the composite CRC, which often requires experiments to determine these characteristics. Especially in the early age of the carbon concrete strengthening layer, when it is necessary to reapply loads on the strengthened element as soon as possible.

The research presented in this paper aims to determine the properties of carbon textile reinforced concrete at an early age under the influence of bond stress, by conducting experimental tests on samples aged four, five, seven and ten days. Then evaluate and interpret the test results and display the material properties of textile concrete at an early age.

3. Research methodology

In order to achieve the research goal, the experimental method was used. Executable samples were made from textile reinforced concrete (TRC) according to the standards recognized in the research centers of the Universities of Dresden and Aachen. The samples were tested at the age of four, five, seven and ten days, and then the results of the experiments were evaluated and the results were collected.

4. Scope of the experiments

We conducted single-sided textile pull-out tests (SPO), see e.g. [20], [21], [22], [23] on concrete specimen with carbon textile reinforcement up to a yarn fineness of 3,300 tex, which were had an impregnation based on Epoxy resin . The experiments had the following goals [11]:

- Determination of the bond behavior under uniaxial tensile loading;

- Determination of the bond flow-crack opening relationship of the composite Material as basis for the calculation of the bond stress-slip relation as bond parameter;
- Determination of end anchorage and lap lengths;
- Comparison of different material combinations and test ages.

5. Test specimen

5.1. Materials

Carbon textile reinforced concrete is a composite material consisting of a (fine-graine) concrete and a non-metallic reinforcement embedded in the matrix, such as textile fabrics made of carbon, glass or basalt fibers.

5.1.1. Carbon textile reinforcement

Carbon is one of the typical materials used in TRC. The form in which these materials are then used as reinforcement depends heavily on the intended use and the technical framework conditions. Basically bars and fabrics processed on textile machines are used. These fabrics are very thin network structures made of fiber strands with different close-meshes, which are produced in multi-stage manufacturing processes and can than be delivered to the construction site as rolls or mats. Several thousand up to approximately 50,000 individual carbon fibers are combined into a yarn in a special manufacturing process, processed into a lattice structure and soaked e.g. [24]. These fabrics or mats are characterized by a wide variety of properties in terms of load-bearing capacity, flexibility, deformability and resistance to temperatures.

For the own tests, the textile "SITgrid 040" from solidian GmbH (Germany [25]) was used to manufacture the test specimens. Table (1) shows the characteristics of the textile reinforcement [26]. Similar textile reinforcement can also be found in [25].

Table (1) Characteristic data of the textile reinforcement [26]

Material		
Fiber material	Carbon	
Impregnation	Epoxy resin	
Geometry		
Shape	Panel	
Dimensions[m]	2.0 × 1.25	
	Longitudinal	Transversal
Centre distance of the rovings [mm]	12.7	16
Cross-section of the yarn [mm^2]	1.81	0.45

Material		
Cross-section of the reinforcement [mm^2/m]	141.02	28.02
Specifications		
	Longitudinal	Transversal
Tensile strength of the roving [N/mm^2]	> 4,000	> 4,000
Tensile strength [N/mm^2], *avg.*	3,300	3,550
Modulus of elasticity (reinforcement) [N/mm^2]	> 220,000	> 205,000

5.1.2. Fine-grain concrete

In the course of the spread of carbon reinforced concrete, the term fine(-graine) concrete was coined. In terms of composition, it is a mortar. Since its properties mostly correspond to high-performance concrete, the term fine concrete seemed more appropriate.

In building strengthening, the workability and sprayability of the concrete play an important role. For this purpose, inter alia, a suitable product was developed with TF10 TUDALIT from PAGEL (former designation; since summer 2021: TF10 CARBOrefit fine-grain concrete [27]). Other concretes are also used in precast construction. Due to the corrosion resistance, textile reinforcements can be installed without the usual concrete cover, which saves a significant amount of weight.

The concrete has several functions in the composite material CRC. Choosing the right concrete is therefore important. The PAGEL TF10 (grain size 0–1mm) is an example of a special development and application. In addition to the special fabric, this fine concrete is the central element for strengthening with carbon reinforced concrete according to the existing general building authority approval [28], [29].

The PAGEL TF10 was used to manufacture the test specimens. Fine concrete samples must fulfil the characteristic data listed in table (2) depending on the age of the hardening according to DIN EN 1015-11:2020-01 [30].

Table (2) Technical data of the fine concrete PAGEL TF10 [27]

Technical data		TF10	
Grain size		mm	0–1
Layer thickness		mm	3–30
Amount of water	max.	%	14
Consumption (dry mortar) approx.		kg/(m^2.mm)	1.9
Fresh mortar raw density approx.		kg/m^2	2,150
Processing time approx.	+ 20 °C	min	60
Measure of extension DIN EN 13396-1	5 min	mm	170–210
Swelling	24 h	Vol.-%	≥ 0.1
Compressive strength*	1 d	N/mm^2	≥ 15

Technical data		TF10	
	7 d	N/mm^2	≥ 40
	28 d	N/mm^2	≥ 80
Bending tensile strength*	1 d	N/mm^2	≥ 3
	7 d	N/mm^2	≥ 6
	28 d	N/mm^2	≥ 8
E-Module (static)	28 d	N/mm^2	≥ 25.000
*** Testing of bending tensile and compressive strength in accordance with DIN EN 196-1**			

The composition and properties of the fine concrete as well as the process-technical parameters for the manufacture using the hand lamination and spraying process must correspond to the specifications of the German Institute for Building Technology [31].

5.2. Geometry

The number of specimens was a total of 40 divided into 4 test series. A test series comprised at least 10 test specimens. The test specimens consisted of one layer of textile reinforcement in a TF10 concrete matrix and had a rectangular shape, Figure (1). The textile was arranged flat and parallel to the sample surface and in the middle in the direction of the sample thickness and the direction of the textile to be examined runs parallel to the length of the sample. The rovings were arranged symmetrically in the direction of the specimen width and so that one roving lies in the center of the specimen. The test specimen should contain at least 3 rovings.

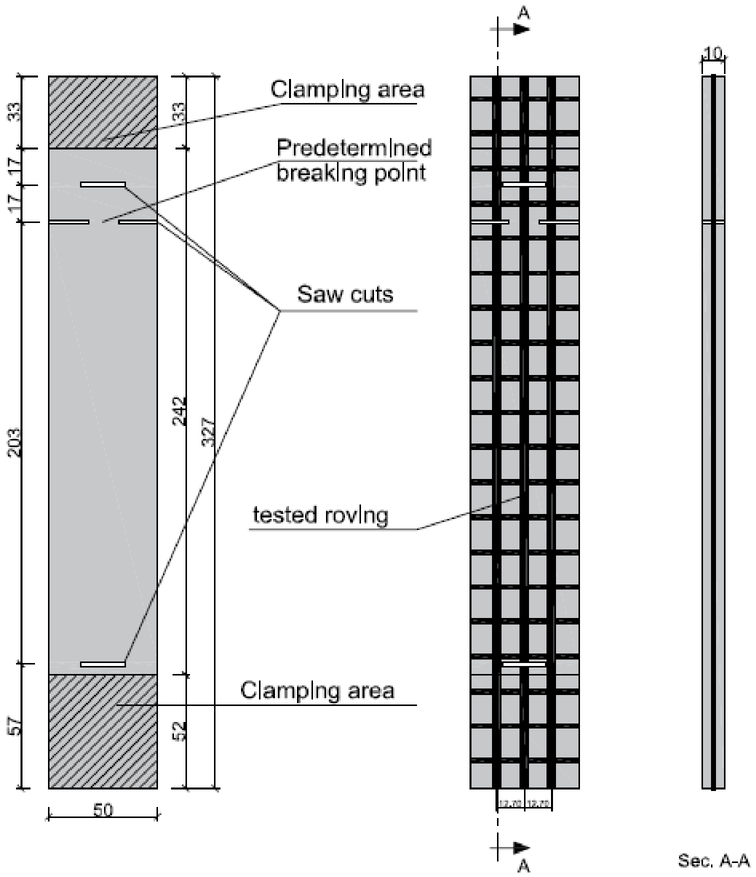


Fig. (1) Test specimen [Researcher]

The width of the sample should be at least 50 mm. The thickness of the sample depends on the concrete cover required for the system of textile reinforcement and concrete matrix, but should be at least 10 mm. The length of the test specimen was approx. 350 mm.

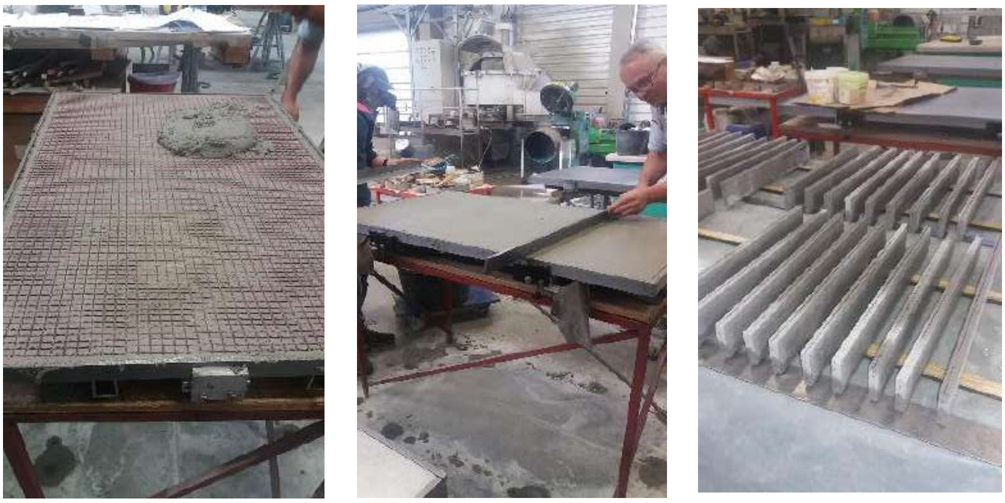
Only one roving was tested within the textile structure. This was sufficiently anchored in the lower long part of the sample. In its upper short section, a defined short anchoring length $L_{E,o}$ can be forced to pull out the roving. $L_{E,o}$ was determined by a saw cut outside of the clamping fixture with a severing of the roving to be tested. At the bottom, the upper anchoring area $L_{E,o}$ was limited by the arrangement of a predetermined breaking point with the aid of a saw cut on both sides. The size of the upper anchoring area was usually chosen with the single spacing of the cross rovings.

The cross roving is in the middle of the upper anchoring area. This enables the composite behavior of the rovings to be checked in sections, taking into account the influences from textile processing. For safe handling of the samples, the size of $L_{E,o}$ should not be less than 14 mm.

5.3. Production and curing

Depending on the concrete matrix used, it can be produced by casting, laminating or spraying. The level and symmetrical position of the textile must be ensured by suitable measures. In the case of pourable concretes, this can be done, for example, by using spacers or clamping the edge of the textile.

However, spacers must not be arranged in such a way that they touch the roving that is checked later, Figure (2).



a b c

Fig. (2) Concreting (a & b) and then sawing (c) the CRC pull-out specimen [Researcher]

Production was initially carried out as large-format panels in smooth, non-absorbent formwork (e.g. steel or coated wood). The top surface of the panels was smoothed. The panels initially remained in the formwork for 1 to 3 days to prevent them from drying out, were then stripped and were to be kept wet until the third day as panels or cut to size. The individual test specimens were cut from the plate one day before the test of the 4 d series was carried out using a water-cooled, diamond-tipped saw. A symmetrical yarn arrangement must be ensured in the test direction. Avoid sawing individual threads in the test direction. The panels or test specimens were stored in the climatic chamber at 20 °C and 65% relative humidity until the test date is upright surrounded by air [30].

Alternatively, with suitable, low-shrinkage concrete matrices, production in individual formwork is possible with otherwise the same test specimen storage.

The saw cuts within the specimen were made using a rotary tool (e.g. dremel). The upper and lower saw cut must completely cut through the roving to be examined. At the predetermined breaking point, the remaining concrete cross-section should be less than 1 cm² and contained only the roving to be tested. Here the test specimen should be stabilized by filling the saw cuts on both sides with PU foam until the test.

6. Experimental setup

The load was introduced via a clamping device on the top and bottom of the specimen outside the extension areas. This was connected to the testing machine in an articulated manner in the short upper extension area. At the lower end, the specimen was clamped directly into the tensile testing machine. The size of the uniform contact pressure was determined in such a way that the specimen did not slip in the load application cpnstruction and the compressive strength of the specimen was not exceeded.

The crack opening was measured with two displacement sensors with a small measuring length placed in the middle on both sides of the specimen over the predetermined breaking point. The displacement sensors must be attached in such a way that they cannot slide, even on smooth sample surfaces. The force was measured by a load cell on the top of the testing machine. The dead weight of the load application structure and the test specimen section above the predetermined breaking point must be taken into account in the test evaluation.

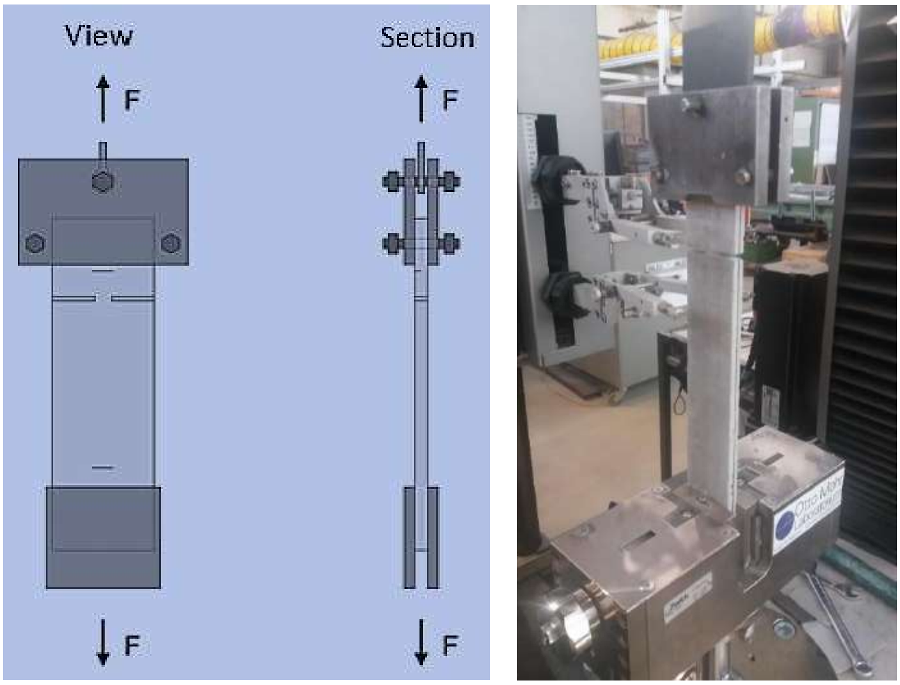


Fig. (3) Experimental setup [Researcher]

7. Experimental procedure and measured variables

The tests were carried out in a tensile testing machine (Zwick 100) of accuracy class 1 and a suitable (low) load capacity (max. 1.0 kN) [32]. The test specimen can be additionally stabilized by suitable measures during the installation of the load introduction as well as during the installation in the testing machine (e.g. attaching files clips over the two-sided saw cuts at the predetermined breaking point).

After installing the specimen, the PU foam filling was removed (e.g. with a suitable, fine saw). The loading then took place in a path-controlled manner and a speed of 1 mm/min until a crack opening of 3 mm was reached. This was followed by a visual check of the roving surface and then, for determining the anchoring length l_{Eo}, a complete extraction of the tested roving from the upper anchoring area with an associated pull-out speed of 10 mm/min. In addition to the machine force F and the machine path s, the crack opening w in the area of the predetermined breaking point by means of extensometers clamped on both sides was recorded. The measuring rate was at least 10 Hz.

A corrective force F_{korr} was determined from the dead weight of the upper load application and the upper part of the sample (through the machine force remaining after the roving had been pulled out completely due to the dead weight of the upper part of the test setup). The force $F_r(w)$ which stressed the analyzed roving can be determined by Eq. (1) [28].

$$F_r(w) = F(w) - F_{korr} \qquad (1)$$

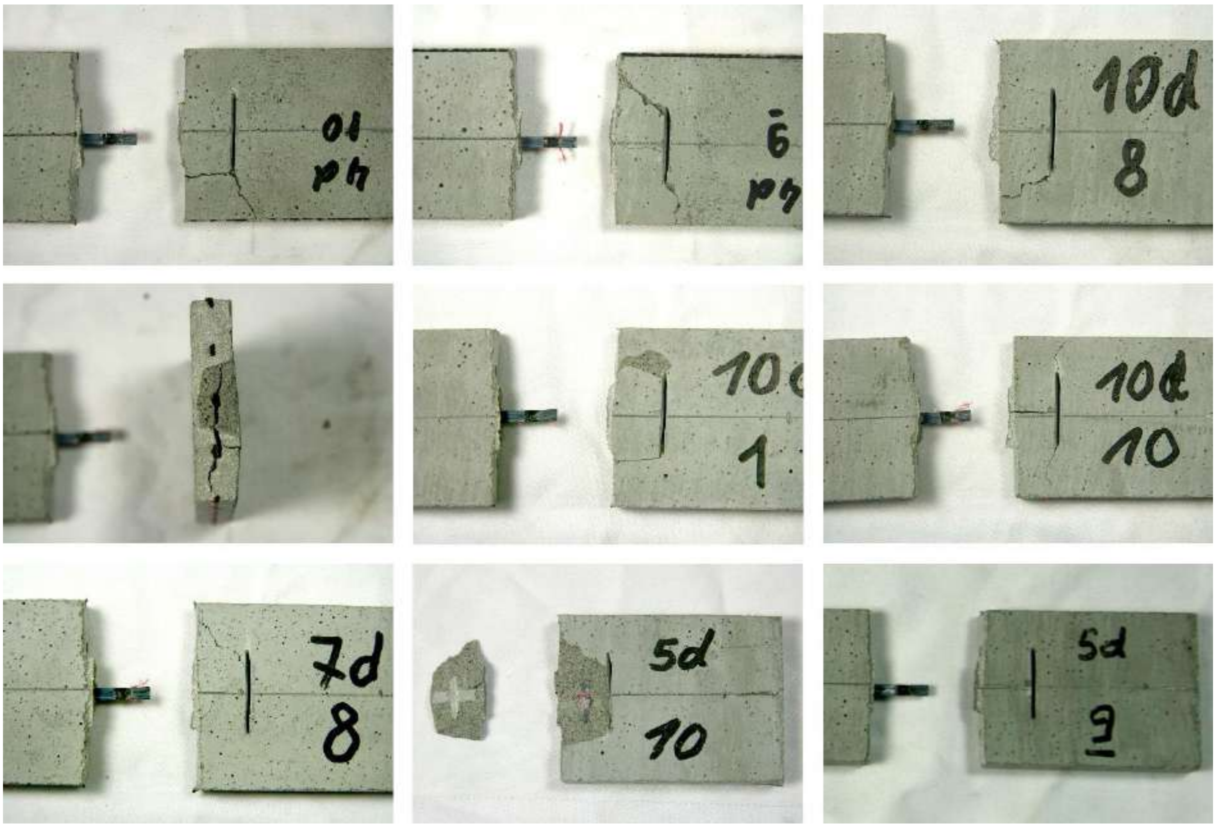
8. Evaluation of the experiment& Interpretation of results

8.1. Failure mechanisms

Knowledge of the various mechanisms that can lead to failure is of central importance for interpreting the tests. Known failure mechanisms, mainly occurring in the upper anchoring area, are listed below:

- Longitudinal cracking in the reinforcement level with flat concrete flaking (Fig. 4a), often denoted as splitting or delamination;
- Longitudinal crack formation perpendicular to the reinforcement plane (Fig. 4b);
- Cross crack formation perpendicular to the reinforcement plane (Fig. 4c);
- Bond failure characterized by yarn pull-out, accompanied by the formation of fine cracks;
- Yarn rupture (if the bond length was sufficient).

Particularly when there was a good bond between textile and concrete, both forms of longitudinal crack formation often occurred in combination. In addition, the form of transverse cracking occurred in some test specimens. Unplanned failure mechanisms were not noticeable in all test specimens. The listed mechanisms cannot always be clearly separated from one another and often occur in combination.



a b c

Fig (4) Observed failure mechanisms in the SPO tests [Researcher]

8.2. Direct results

The direct results are shown in Figures (5)–(8) for all test series.

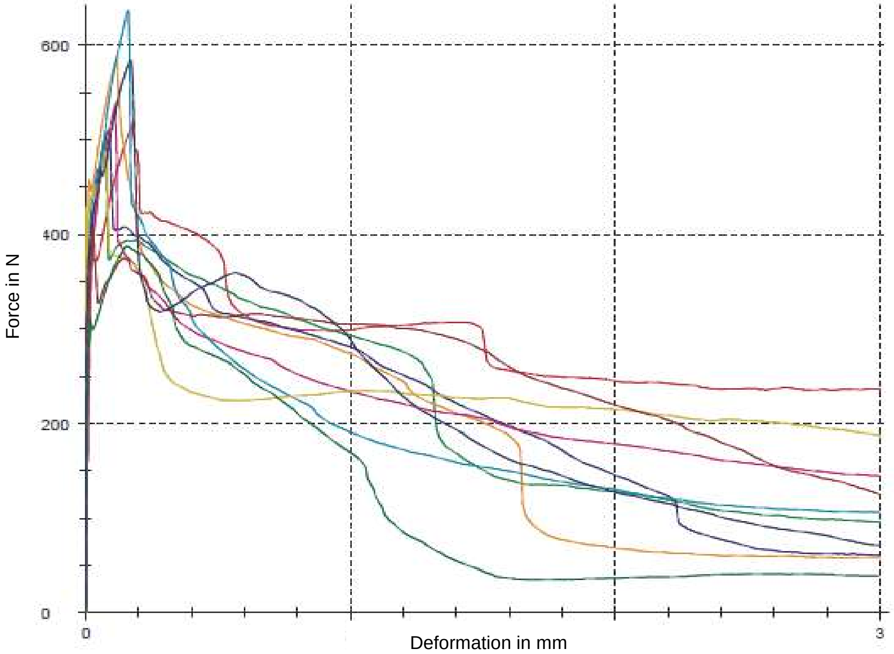


Fig. (5) Direct test results – sample age 4 days [Researcher]

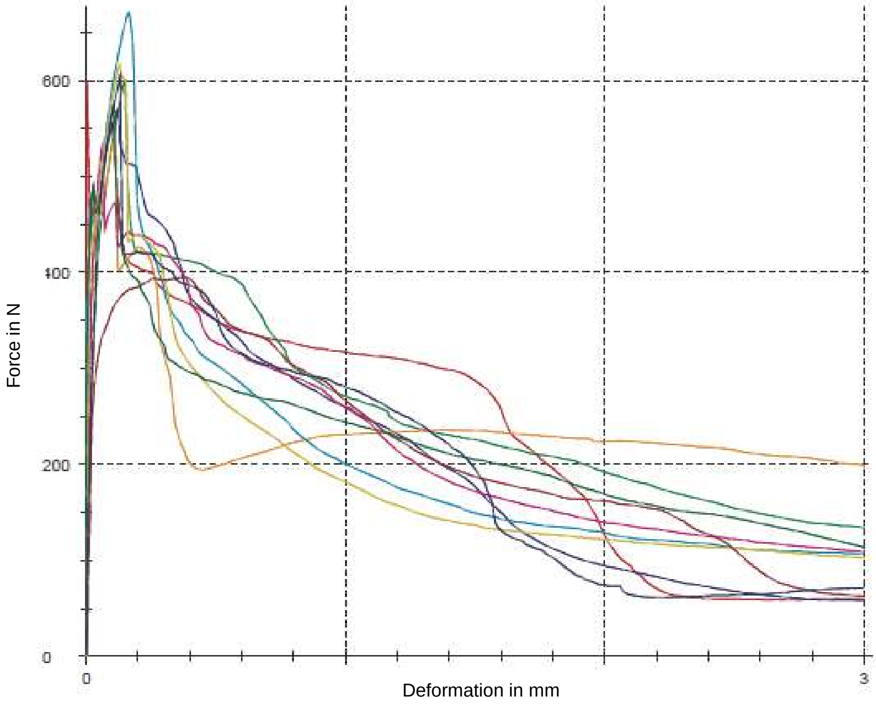


Fig. (6) Direct test results – sample age 5 days [Researcher]

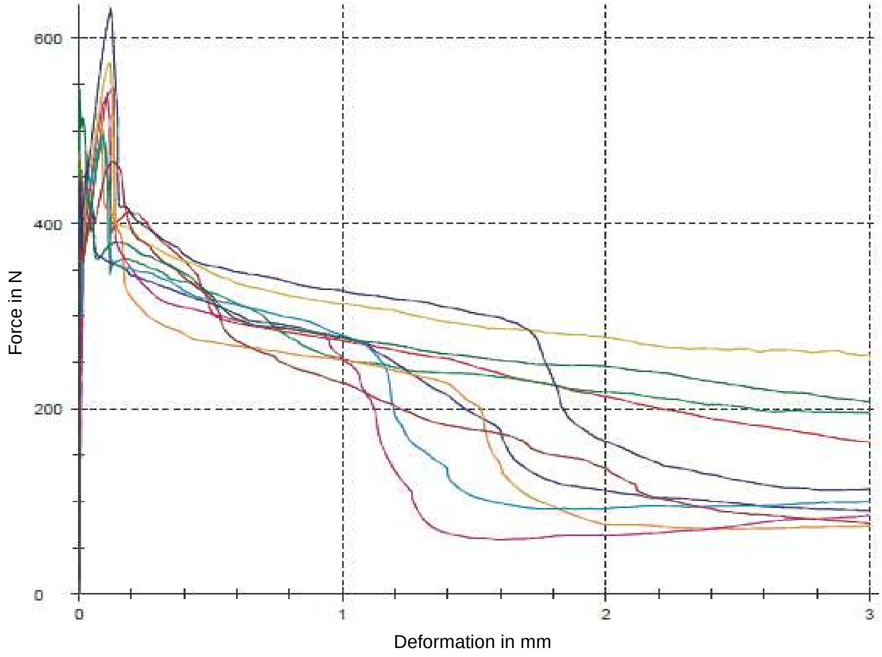


Fig. (7) Direct test results – sample age 7 days [Researcher]

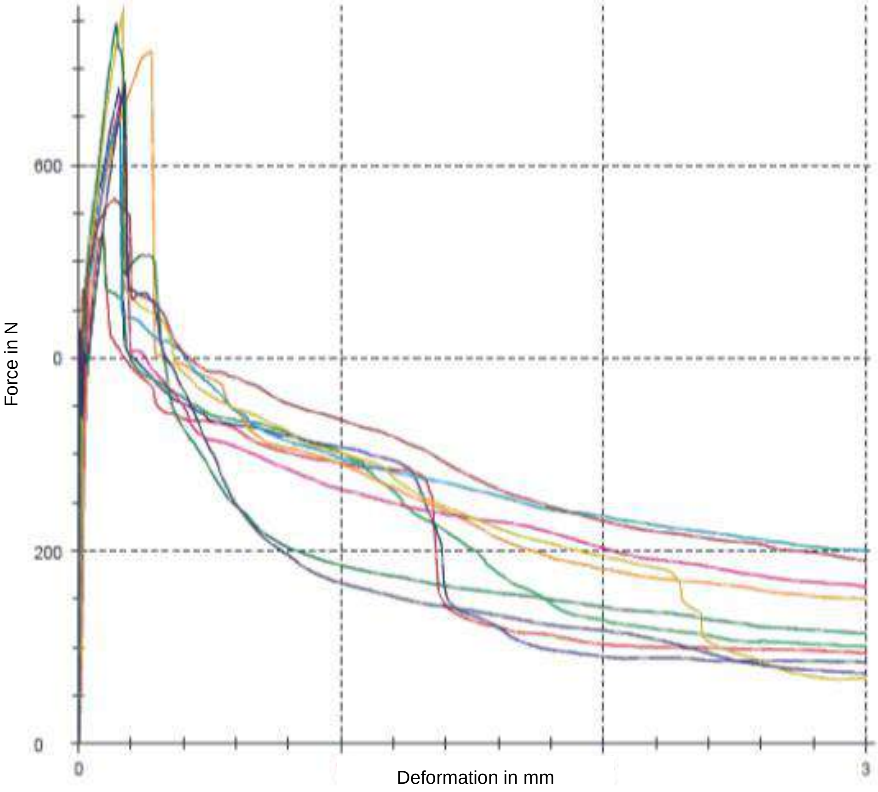


Fig. (8) Direct test results – sample age 10 days [Researcher]

From the relationship between force F and deformation Δl_i of the individual displacement sensors, for the mean force deformation relationship can be derived from each test series.

8.3. Accompanying tests on the fine concrete

Accompanying the SPO tests, trials were be carried out to prove the material properties achieved of the fine concrete. For this purpose, the fresh concrete properties were evaluated and documented. To test the hardened concrete properties, mortar prisms 4 × 4 × 16 cm based on DIN EN 196-1 were produced [33]. At least three values for the flexural tensile strength and at least six values for the compressive strength were determined. Documentation of construction-related tests is shown in Table (3).

Table (3) Characteristic values of fine concrete from routine and accompanying tests [Researcher]

Sample age [d]	Flexural strength R_f [N/mm²]	Compressive strength R_c [N/mm²]
4	5.61	49.9
5	5.83	51.9
7	5.41	55.0
10	5.81	60.8

8.4. Force- and bond flow-crack opening curves (F-w and T-w)

In the results, force-crack opening curves (F-w) are shown and bond flow-crack T opening relationships (T-w) were established. The bond flow T was calculated as follows [12]:

$$T = \frac{F_r}{L_{E,o} - w}$$

With: $F_r = F - F_{korr}$ Actual pull-out force on the roving, see Eq. (1)

$L_{E,o}$ Anchoring length, measured on the pulled roving

w Crack opening

In the following figures (9)—(12), the relations between bond stress (τ) and slip (s_{ge}) as well as the bond flow (T) and the crack opening (w) — derived from the mean force-deformation relationship in Figures (5)—(8) — are shown for every sample of all test series, sorted by the sample age. The third diagram shows the force-anchoring relationships.

The characteristic points T_2 and T_3 of the bond flow-crack opening relationships (see Figure 14) must not fall below the following values [28]:

- individual values $T_{2,i}$; $T_{3,i} \geq 3.96$ N / mm²
- Mean value from the last 10 samples $T_{2,m}$; $T_{3,m} \geq 4.72$ N / mm² (lower green dashed line).

In addition, an upper limit is defined for the characteristic point T_1 of the bond flow flow-crack opening relationship.

- Individual values $T_{1,i} \leq 33.7$ N / mm²
- Mean value from the last 10 samples $T_{1,m} \leq 30.2$ N / mm² (upper green dashed line).

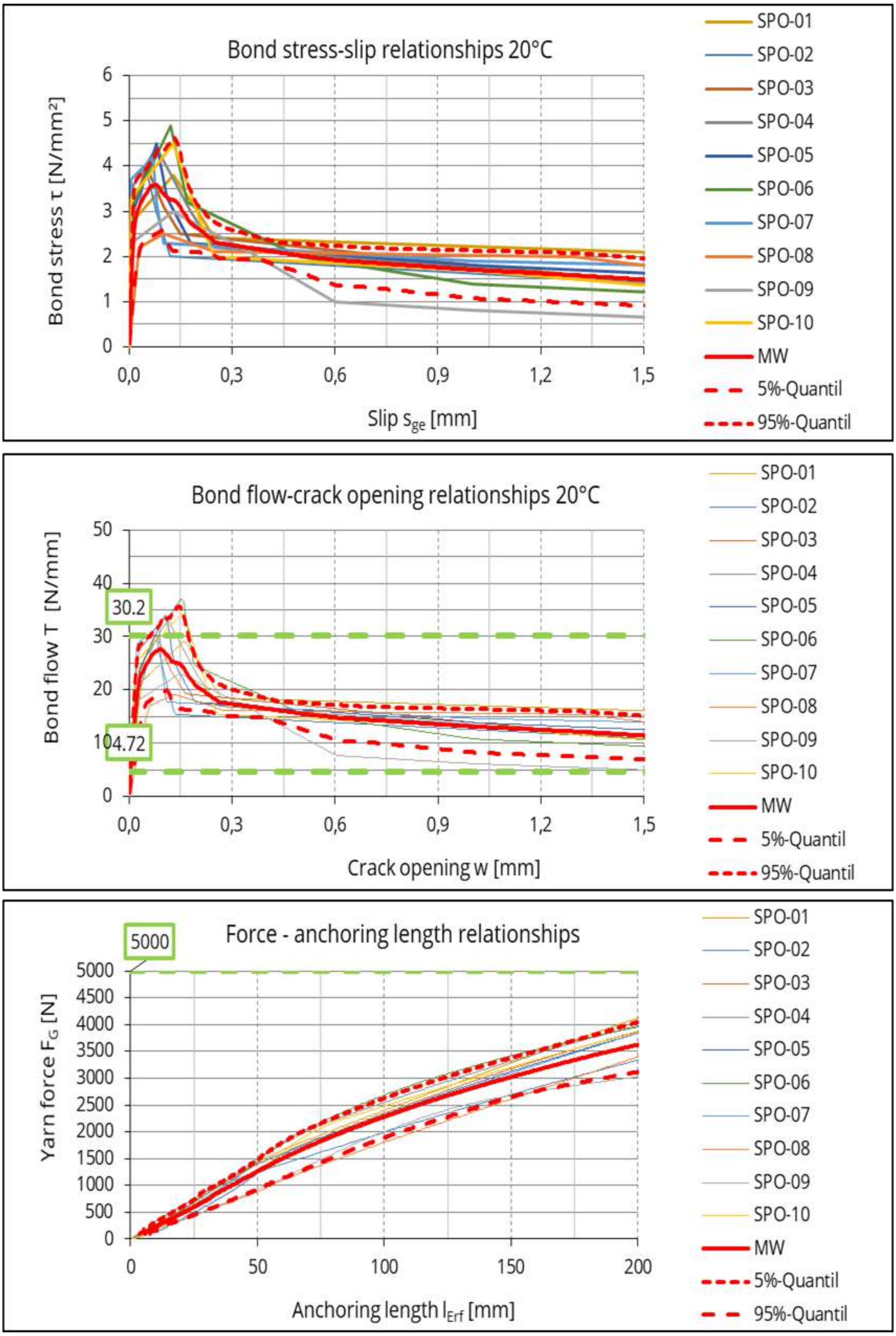


Fig. (9) Results of SPO tests, sample age: 4 d; from top to down: bond stress-slip curve, bond flow-crack opening curve, yarn force-anchoring length curve [Researcher]

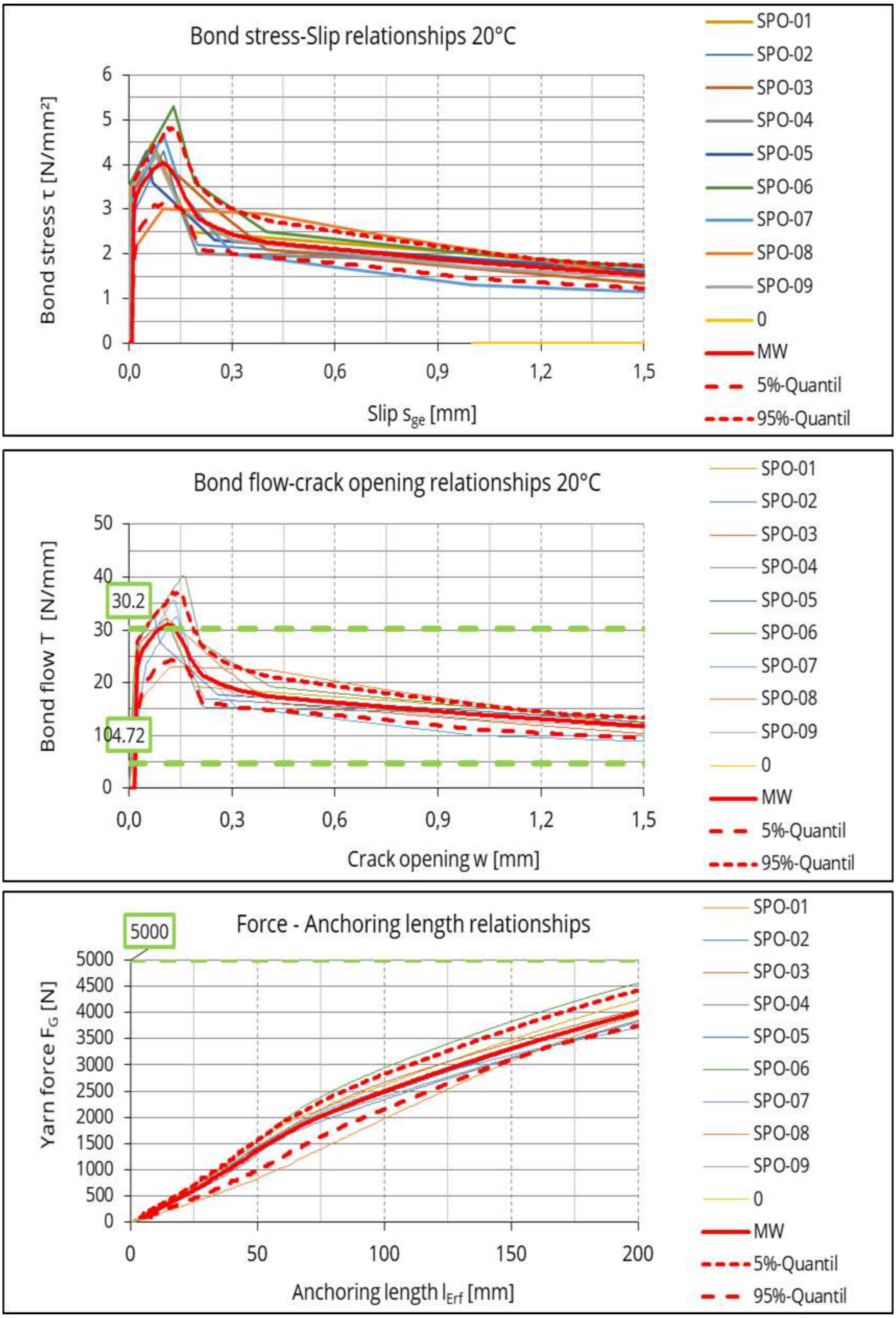


Fig. (10) Results of SPO tests, sample age: 5 d; from top to down: bond stress-slip curve, bond flow-crack opening curve, yarn force-anchoring length curve [Researcher]

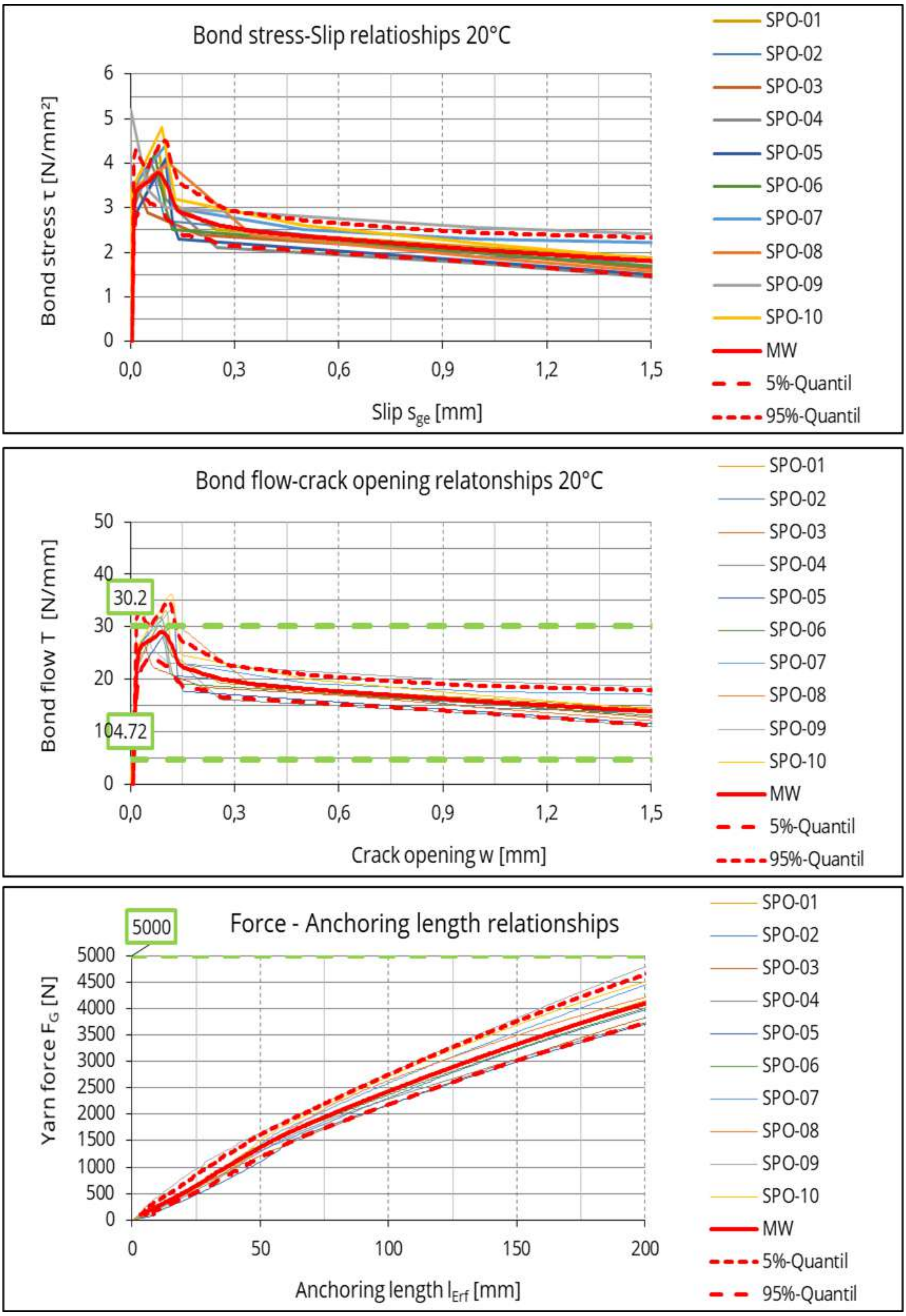


Fig. (11) Results of SPO tests, sample age: 7 d; from top to down: bond stress-slip curve, bond flow-crack opening curve, yarn force-anchoring length curve [Researcher]

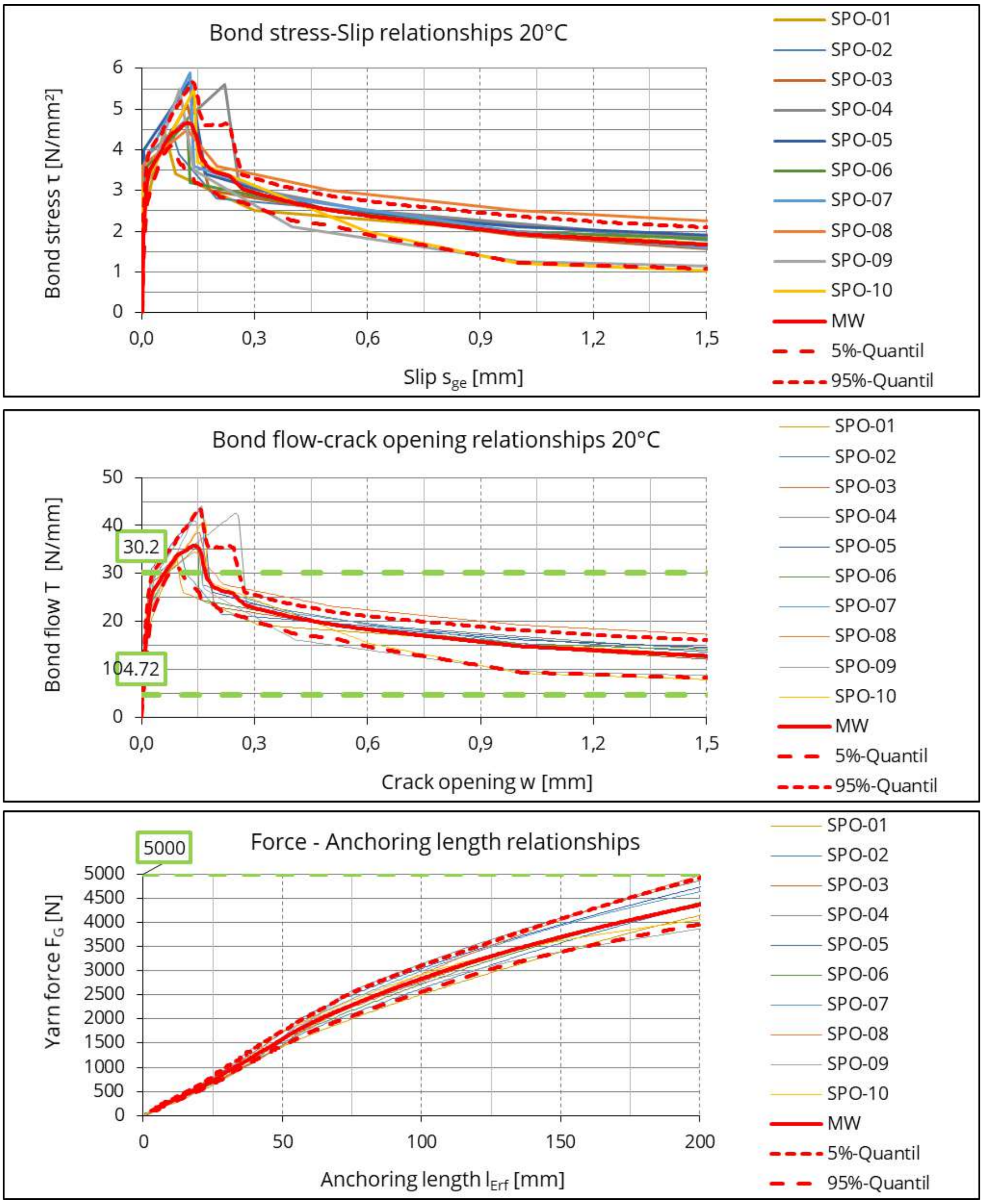


Fig. (12) Results of SPO tests, sample age: 10 d; from top to down: bond stress-slip curve, bond flow-crack opening curve, yarn force-anchoring length curve [Researcher]

Figures (9)–(12) clearly show the typical three areas of τ-s_{ge} resp. T-w lines determined in SPO tests, see Figure 13 [28].

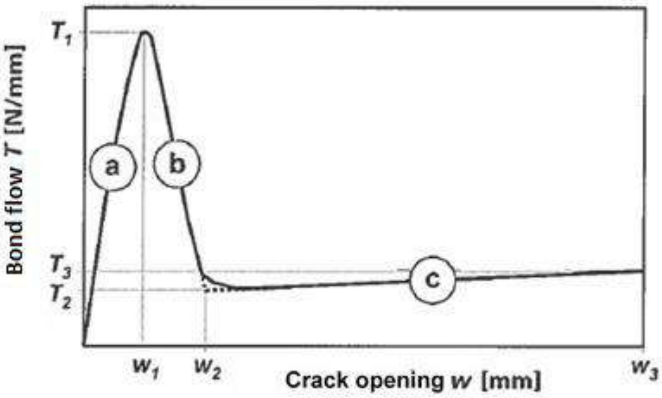


Fig. (13) Principal course of a bond flow-crack opening curve [29]

While points T_1 and T_2 result when the maximum value of the pull-out resistance is reached and the transition from the sloping branch (b) to area (c), point T_3 describes the pull-out resistance in section (c) with a specified crack opening w_3 of 1.5 mm. In the first section (a) the adhesive bond is activated. The acting forces are transmitted via adhesion in the interface between reinforcement and the concrete matrix. After the adhesive forces have been exceeded, the adhesive bond or adhesive bond fails successively, with the yarn becoming detached from the fine concrete matrix (b). This is usually accompanied by a drop in composite resistance. In the third section (c) the yarn is completely detached from the matrix.

Figure (14) shows the mean value curves of the bond flow-slip relationships for the different specimen ages.

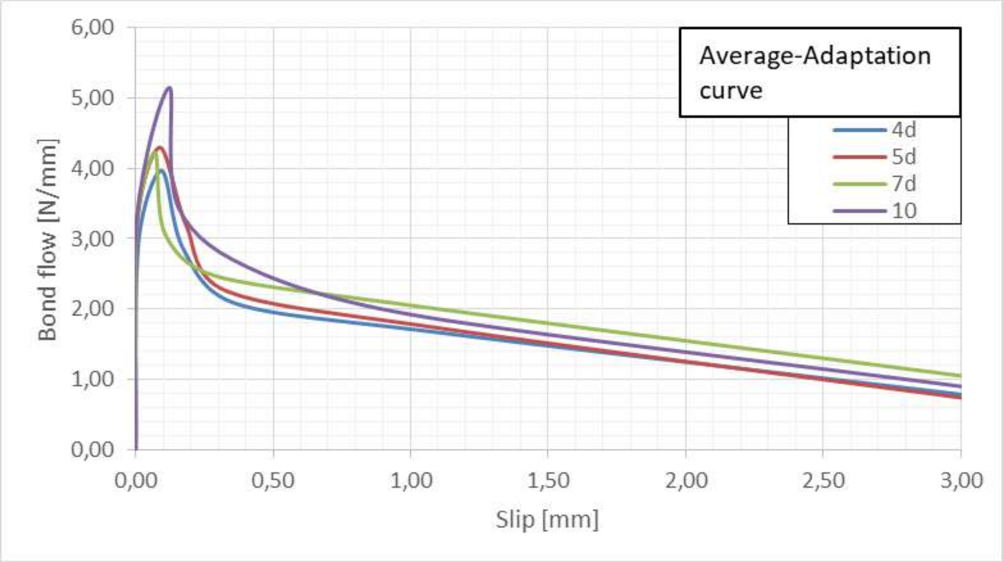


Fig. (14) Bond flow-crack opening curves – mean value curves for each series [Researcher]

8.5 Influence of the age of the concrete

The maximum force at the 1.5 mm slip increases with the age of the concrete, Figure (15). By inducing the mean value curve, a maximum force F_{max} (1.5 mm) of 5552 N can be expected in 28 d old samples. As expected, the force corresponding to the slip value of 1.5 mm increases with increasing age of the sample and is expected to reach the value 5552 N at the age of 28 days.

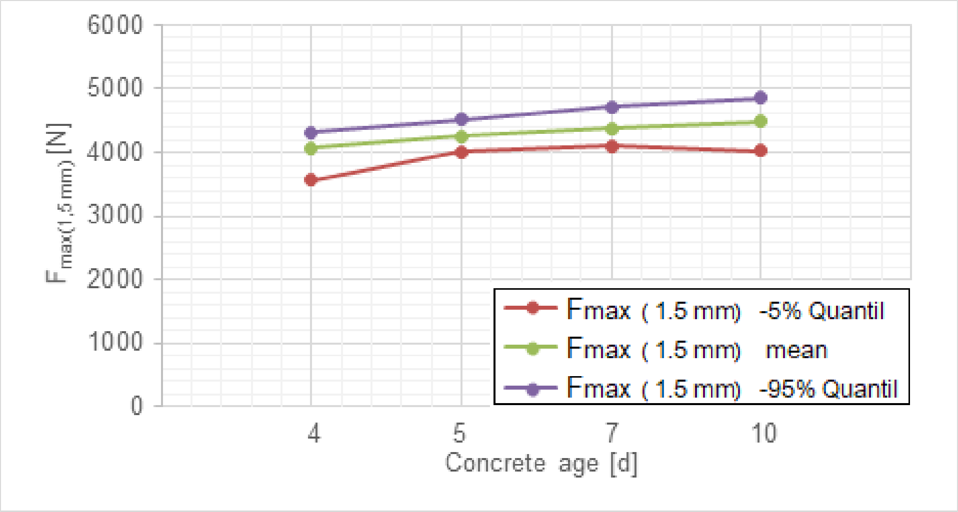


Fig. (15) Maximum force-concrete age curve at 1.5 mm slip [Researcher]

Figure (16) shows the influence of the age of the concrete on the anchoring length for an anchoring tensile force per yarn of 5,000 N. The anchoring length decreases significantly with increasing age of the concrete. If the concrete is 28 days old, an anchorage length of 75 mm is to be expected.

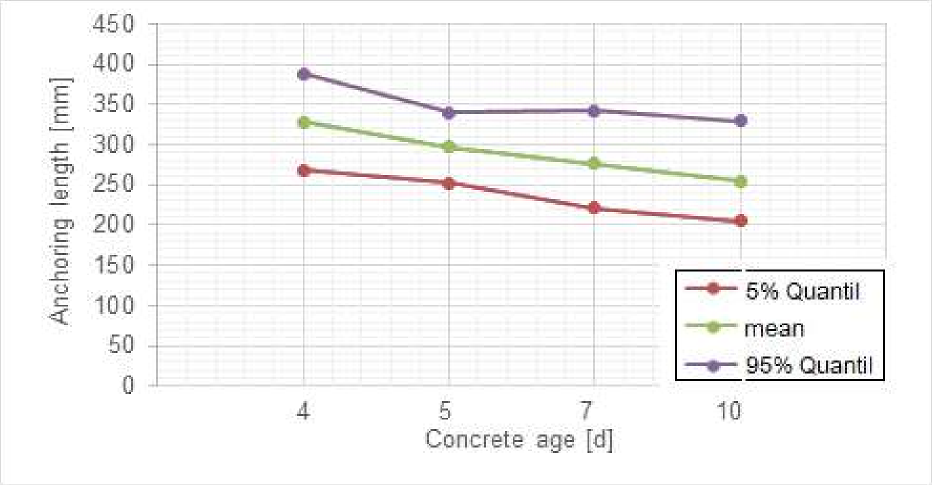


Fig. (16) Anchoring length-concrete age curve – yarn tensile force to be anchored 5000 N [Researcher]

Figure (17) shows the minimum and maximum crack spacing-concrete age curve. Both values decrease with increasing concrete age. In addition, with the increase in the sample age, the value of the spacing between cracks decreases and the value of the coherence field length decreases as well. In this case, the behavior of carbon-reinforced concrete is similar to that of steel-reinforced concrete.

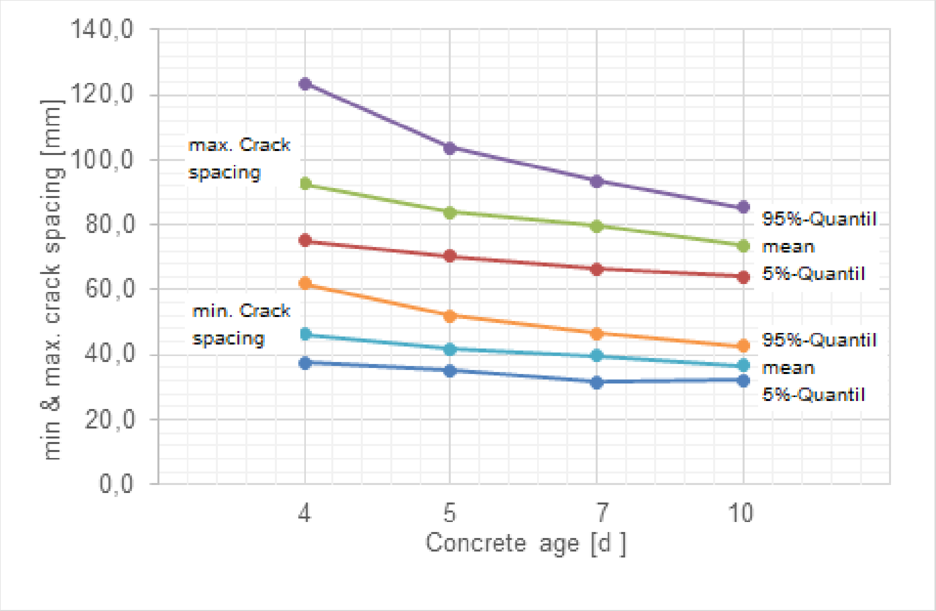


Fig. (17) Minimal and maximal crack spacing-concrete age curve [Researcher]

9. Summary

The test results presented in this documentation for SPO test on carbon reinforced concrete with textile reinforcement expand the results of many years of research and testing at the Institute of Concrete Structures at the TU Dresden by the aspect of bond in young concrete age. These results support the future preparation of standards and approvals. They are of particular interest for those structural elements where the load has to be applied at an early concrete age (e.g. for the strengthening of bridges in combination with limited barrier times). As expected, the force corresponding to the slip value of 1.5 mm increases with increasing age of the sample and is expected to reach the value 5552 N at the age of 28 days. In addition, with the increase in the sample age, the value of the spacing between cracks decreases and the value of the coherence field length decreases as well. In this case, the behavior of carbon-reinforced concrete is similar to that of steel-reinforced concrete.

10. Outlook

The information on implementation and evaluation should enable successful testing and determination of important material properties. Some detailed questions still need to be clarified. The focus is first on the influence of the species and the quality of the impregnation and the resulting stiffness relationships between the textile and the concrete matrix.

Acknowledgement

The work was conducted during my research stay as a research assistant at the Institute of Concrete Structures at the Technical University of Dresden in the years 2019–2021. The author thanks the Alexander von Humboldt Foundation for funding the project. Many thanks also go to the employees of the Institute of Concrete Structures and the Otto Mohr Laboratory, headed by Professor Manfred Curbach, who played a very active role in the preparation of the work presented.

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