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Accelerated ageing of textile reinforced concrete (TRC)

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Abstract. The durability of textile reinforced concrete (TRC) applied in innovative lightweight sandwich elements has been investigated in the framework of EC supported FP7 project, H-House (Healthier Life with Eco-innovative Components for Housing Constructions). This paper presents the experimental results from two studies related to the effects of accelerated ageing on selected textile fabrics and on the composite form of TRC. Firstly, the durability related to the alkali-resistance of three commercially available textile fabrics of carbon, basalt and alkali-resistant glass (AR-glass) was studied by means of accelerated aging and direct tensile tests based on ISO 10406-1 and alternative boundary conditions. Furthermore, it was also of interest to observe if the tested basalt and AR-glass textile fabrics would have differing material degradation when faced with accelerated testing while being embedded in a concrete matrix. Accordingly, thin rectangular TRC panels reinforced by basalt and AR-glass were aged in three different conditions for approximately 30 days (i.e. 20°C, 40°C and 60°C in water) and thereafter underwent uniaxial tensile testing. The external appearance of the textile reinforcement samples was examined before and after immersion, for comparison of colour, surface condition and change in shape. To characterize the change in mechanical properties, direct tensile and uniaxial tensile tests were performed on both unaged and aged textile reinforcement and TRC samples, respectively. The main conclusions from this study are that the tested carbon textile samples appear to have superior alkali resistance, which indicate promising long-term durability of the reinforcement in a concrete matrix. Also, the coating applied during textile production is a governing factor affecting the degradation of textile reinforcement in an alkaline environment particularly related to the tested AR-glass and basalt products. It was found challenging to specify one test method for different types of textile materials due to their differing degradation processes.

Introduction

The H-House (Healthier Life with Eco-innovative Components for Housing Constructions) project, funded by European Commission, aims to develop a number of new building systems suited to a society where environmental awareness and a high degree of living comfort are both required [1]. The concept of the project is to develop new building components for external and internal walls for new buildings and renovation. Within the project framework, an innovative lightweight sandwich element for new construction has been developed using textile reinforced concrete (TRC) combined with a cementitious based insulating material. TRC acts as both a facing and load bearing layer within the sandwich element. As such, a TRC facing layer is exposed to the outdoor environment, thereby making it important to understand the durability performance of this composite material.

The durability of fiber-based reinforcement materials, such as fiber reinforced polymer (FRP) rods and textile reinforcement, is typically assessed by means of accelerated ageing.

Accelerated ageing related to the alkali resistance typically consists of immersing the reinforcement sample in a simulated or actual concrete pore solution while being exposed to high temperature [2, 3]. To determine the effect of the accelerated ageing, mechanical tests such as tensile tests can be conducted on fibre-based reinforcement samples before and after ageing. For textile reinforcement cast in concrete, samples can be exposed to varying temperatures or moisture conditions in a climate chamber followed by the quantification of loss of tensile strength and bond through various mechanical tests [4, 5]. Despite the fact that there are a number of existing studies made on the durability performance of fibre-based reinforcment materials for concrete, these results are often non-comparable due to e.g. differences in material composition and testing parameters.

The purpose of this paper is to present experimental results related to the durability of the materials being incorporated in the developed composite elements. In this study, the durability of TRC in terms of alkali-resistance was investigated on the material and composite levels. It is to say that on the material level, the suitability of using selected textile reinforcement materials readily available on the market, i.e. made of carbon, basalt and AR-glass fibres, was investigated through accelerated aging and direct tensile tests based on ISO 10406-1 [6]. As for the composite level, these tested textiles were embedded in a concrete matrix, exposed to given accelerated ageing conditions and thereafter tested under uniaxial testing as per the recommendation of RILEM TC 232-TDT [7]. Overall, it is of key interest to determine which type of textile reinforcement would present the most promising long-term durability whilst being exposed to an alkaline environment.

Experimental Investigation

Within this scope of work, experiments were conducted to investigate the durability of selected textile reinforcement products on both material and composite levels. The two experimental investigations can be specified accordingly: 1) accelerated ageing on material level and 2) accelerated ageing on composite level.

Study 1 – Accelerated ageing on material level. The materials studied consisted of AR-glass, basalt and carbon textile reinforcement grids which were primarily selected based on the current availability of commercial products (refer to [8] for more product information). The durability related to the alkali-resistance was investigated for these products by means of accelerated testing. Accelerated testing was based on ISO 10406-1 [6], which specifies that the given specimen should be immersed in an alkaline solution (pH > 13) while being exposed to a temperature of (60 ± 3) °C for 30 days. Alternative boundary conditions were also studied due to the fact that the upper boundary condition prescribed by the standard was found to be too harsh for some of the tested textile products. All test parameters included in this study are summarized in Table 1.

Table 1. Overview of test matrix for Study 1.

Case	Exposure conditions	Temperature [°C]	pH value [-]	Time [days]	Specimens		
					Carbon	Basalt	AR-glass
Reference	Room temperature	20	-	0	C0	B0	A0
1	High temperature + high pH (ISO 10406-1)	60	14	5	C1-5	B1-5	A1-5
				10	C1-10	B1-10	A1-10
				20	C1-20	B1-20	A1-20
				30	C1-30	B1-30	A1-30
2	High temperature + neutral pH	60	7	30	C2	B2	A2
3	Low temperature + high pH	20	14	10	C3	B3	A3
4	Low temperature + neutral pH	20	7	10	C4	B4	A4

	Performed ageing only
	Performed ageing + tensile test
	Not tested

The external appearance of the textile reinforcement specimens was examined before and after immersion, for comparison of colour, surface condition and change in shape. Moreover, the mechanical strength of the specimens was also quantified using direct tensile tests on both non-aged and aged samples based on ISO 10406-1 [6]. From this test, the tensile strength, ultimate strain and tensile rigidity can be determined for each specimen type. The test setup applied in this work is exemplified in Figure 1 and a detailed description of the specimen preparations and test specifications is provided in [8].

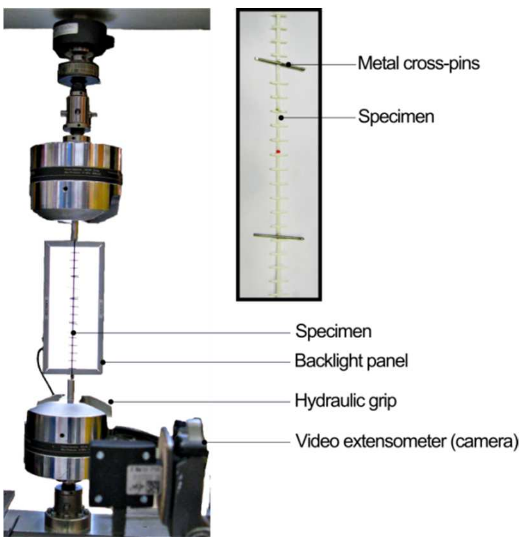


Figure 1. Direct tensile test setup applied in Study 1 (from [8]).

Study 2 – Accelerated ageing on composite level. The effect of accelerated ageing on the composite level was investigated for TRC. TRC rectangular panels (700 x 100 x 20 mm) reinforced by two layers of either basalt or AR-glass textile reinforcement were cast in a fine-grained concrete matrix developed in this project. The TRC specimens were cured for 28-30 days under three different conditions: 1) 20 °C in water (reference), 2) 40 °C in water and 3) 60 °C in water. It was of further interest to observe if basalt and AR-glass textiles tested in Study 1 would have differing material degradation when faced with so-called accelerated testing while being embedded in a concrete matrix. In reality, the pH level of the pore solution found in the matrix is not as elevated as that specified by the ISO 10406-1 [6]; therefore, it was thought that accelerated ageing of the composite could represent more realistic conditions. It should be noted that carbon textile reinforcement was excluded from Study 2 as it was observed in Study 1 that this given product was generally inert when exposed to extreme alkaline conditions and high temperature.

After sample curing, the tensile load bearing behaviour of the TRC specimens was characterized using uniaxial tensile tests according to the Recommendation of RILEM TC 232-TDT [7]. The specimen configuration and tensile test setup are depicted in Figure 2. The ends of the specimens were clamped between two stiff steel plates, which transfer the load to the specimen by friction. The applied clamp pressure and contact area were chosen to prevent slippage between the clamp and specimen. Additional thin neoprene rubber sheets were placed in the contact areas to avoid local stress concentrations. Moreover, the tests were carried out in an electro-mechanical universal testing (Sintech 20D). The tests were conducted as displacement controlled, whereas the load and machine displacement were recorded in a data acquisition system (sampling rate of 10 Hz). The specimens and clamping devices were aligned in a frame to ensure centric loading and the clamps were hinged connected to the test machine.

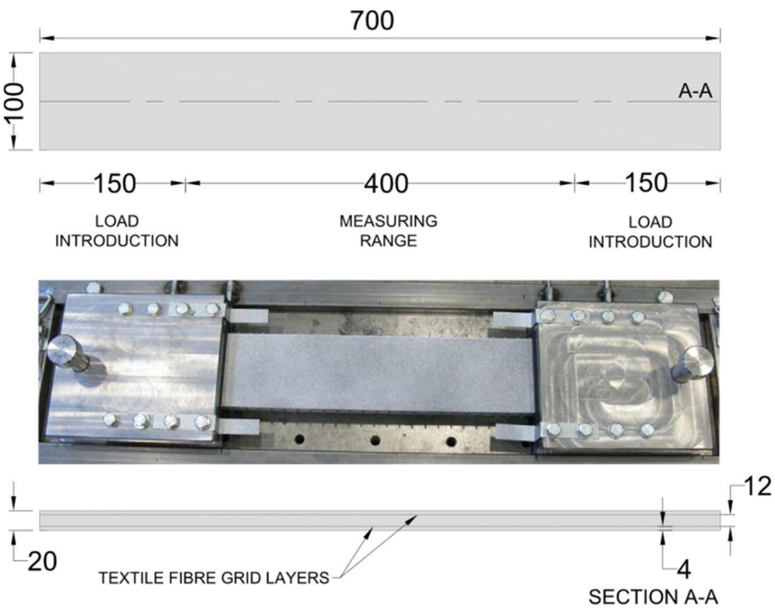


Figure 2. Panel dimensions and clamp detail (left) and test setup for uniaxial tensile test (right).

Experimental Result Summary

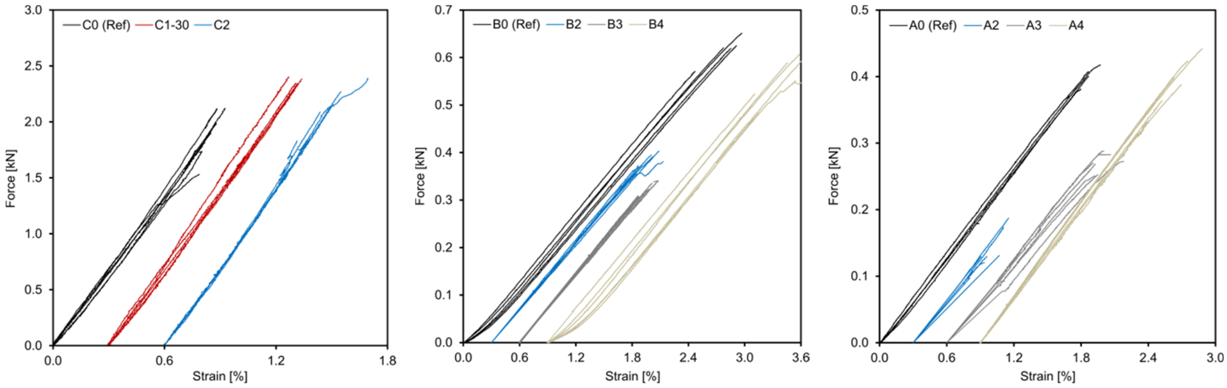
Results from Study 1. The experimental results from Study 1 were analysed according to changes in visual observations and mechanical properties before and after accelerated ageing.

Visual Observations. For the tested carbon textile reinforcement samples, no significant visible change of colour, surface structure or texture was observed for all exposure cases.

However, colour change was apparent on the basalt samples aged according to the conditions related to Cases 1 and 2 (B1, B2). The cause of colour change could have been caused by the lifting of the textile coating to the surface. Also, the samples were unable to be tested mechanically as they broke during the ageing process, apart from B1-5 and B2. For Cases 3 and 4 (B3, B4), the coating appeared to build up at the cross-points along with minor colour change on the surface. The stiffness of B3 samples appeared to be weaker however as these could be ruptured by a minimal pulling force at the cross-points.

As for the AR-glass reinforcement samples exposed to Cases 1 and 2 (A1, A2), these generally lost stiffness and cross-threads. Specimens exposed to Cases 3 and 4 (A3, A4) remained in tact after immersion, while samples exposed to Case 3 (A3) were marked by a wavy structure.

Tensile Test Results. Direct tensile tests were performed on both unaged and aged samples based on ISO 10406-1 [6]. The applied load versus strain of the tested textile reinforcement samples are shown in Figure 3. In certain cases, it was not possible to quantify the tensile strength of a given sample due to the extent of material degradation (see Table 1). The direct output of the tensile tests included the ultimate tensile capacity, F_u, and ultimate strain, ε_u. The tensile rigidity, E_A, can be calculated from the load-strain curve as the secant modulus (see [8]).



a) b) c)

Figure 3. Results from the direct tensile tests: carbon textile (a), basalt textile (b) and AR-glass textile (c). For visualization, the initial strain was shifted 0.3%-units relative to each previous case.

In Figure 3, the tensile behaviour is marked by a linear relationship which terminates by means of a brittle failure upon reaching the ultimate stress of the textile reinforcement material. To further analyse the results, the tensile capacity retention rate, R_{ET}, being the ratio between the ultimate tensile capacities of aged sample versus unaged sample, was applied to measure the relative mechanical degradation of the aged samples. A summary of R_{ET} values for the tested samples is provided in Table 2. A more detailed account of these results can be found in [8].

Table 2. Summary of tensile capacity retention rate for tested samples (standard deviation in parentheses).

Case	Exposure conditions	Temperature [°C]	pH value [-]	Time [days]	Tensile capacity retention rate, R_{ET} [%]		
					Carbon	Basalt	AR-glass
Reference	Room temperature	20	-	0	-	-	-
1	High temperature + high pH (ISO 10406-1)	60	14	5	-	3 (2)	33 (7)
				10	-	-	-
				20	-	-	-
				30	125 (2)	-	-
2	High temperature + neutral pH	60	7	30	114 (11)	62 (2)	35 (7)
3	Low temperature + high pH	20	14	10	-	52 (3)	65 (3)
4	Low temperature + neutral pH	20	7	10	-	90 (8)	97 (10)

(dark grey)	Performed ageing only
(light grey)	Performed ageing + tensile test
(white)	Not tested

From the results presented in Table 2, it is difficult to state the significance of the retention rates and how much the degradation is related to the temperature or the alkalinity. As such, the tensile capacity retention rates were statistically evaluated in [8] to gain a further understanding of the data scatter and confidence of the results. The outcome of this statistical evaluation is only summarized in this paper.

The observed increase in tensile capacity for carbon textile reinforcement samples was found to have a significant increase in tensile capacity only for Case 1. This increase is thought to be caused by the stiffening of the textile coating occurring at high temperatures. According to these observations, the tested carbon textile is highly resistant to a high alkaline environment and high temperature.

The basalt and AR-glass samples aged according to Case 1 were only measurable after 5 days of exposure. Besides, the greatest amount of tensile capacity loss (35 %) was observed for AR-glass under Case 2, while it was the case for basalt (52 %) under Case 3. Moreover, it is thought that the difference between the tensile capacity retention of AR-glass (65 %) and basalt (52 %) under exposure Case 3 could be a result of the additionally applied alkali-resistant coating on the AR-glass samples. As such, the applied coating is likely a governing factor affecting the degradation of textile reinforcement in an alkaline environment. This factor could be verified using e.g. microscopy to measure the surface degradation. Lastly, for Case 4, the significance of the loss of tensile capacity for basalt is uncertain, while that of AR-glass is insignificant.

Results from Study 2. Uniaxial tensile tests according to the recommendation of RILEM TC 232-TDT [7] were performed on TRC specimens reinforced by the same AR-glass and basalt textiles tested on the material level in Study 1. Resulting from these tests, load versus global deformation curves are presented in Figure 4, while the main test results are also summarized in Table 3. Four specimens were originally tested for each condition, however the test results were only considered valid if the failure of the specimen took place within the measured gauge length. In some cases, particularly pertaining to specimens cured according to Cases 2 and 3, failure took place in the end anchorage length such that these results were not further considered as representative of the true behaviour. To impede such a failure from occurring in the end anchorage length, the specimens can be additionally reinforced in these areas by means of additional reinforcement or epoxy coating.

Table 3. Mean uniaxial tensile test results (standard deviation in parentheses).

Case	Curing conditions	Reinforcement type	No. cracks	1st crack		Max. displacement
				$P_{cr,1}$ [kN]	$\sigma_{cr,1}$ [MPa]	δ_{max} [mm]
1 (Reference)	20°C, water, 28 d	Basalt	1-2*	7.2 (0.6)	3.5 (0.4)	2.8 (0.9)
		AR-glass	1-2*	6.5 (0.4)	3.1 (0.1)	1.6 (0.2)
2	40°C, water, 30 d	Basalt	1	9.0 (0.8)	4.4 (0.4)	2.1 (0.2)
		AR-glass	1-2*	8.6 (2.3)	4.1 (1.0)	1.9 (0.4)
3	60°C, water, 30 d	Basalt	1-2*	9.2 (0.2)	4.4 (0.1)	1.5 (0.3)
		AR-glass	1-2*	7.0 (2.2)	3.4 (1.0)	1.8 (0.0)

*Some cracks formed in the end anchorage locations which are not representative of the true tensile behaviour.

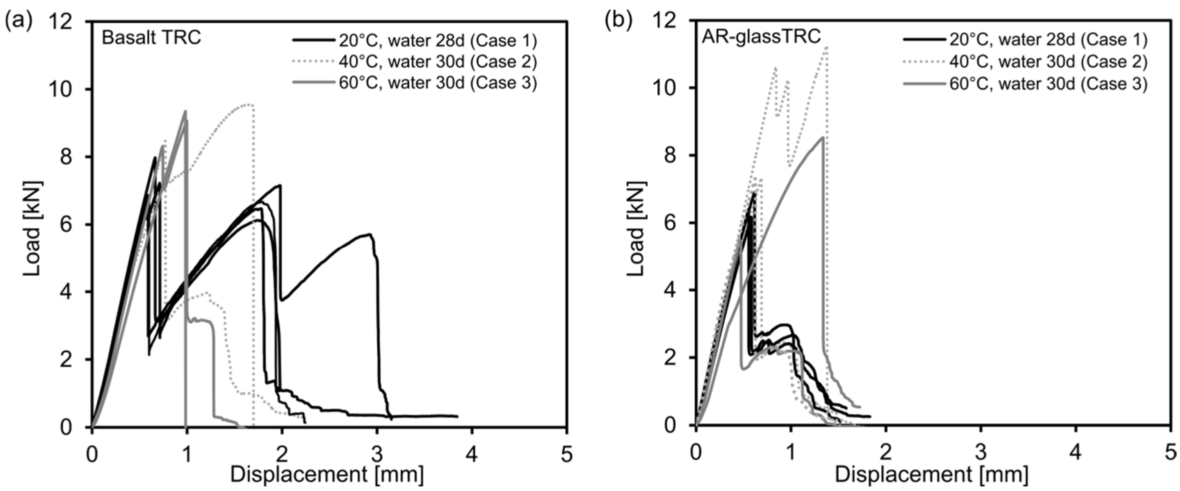


Figure 4. Results from the uniaxial tensile tests: basalt TRC panels (a) and AR-glass TRC panels (b).

From the presented uniaxial tensile tests on TRC, it can be generally concluded that first cracking strength of the concrete matrix, i.e. tensile strength, increased due to the temperature increase during curing for all cases. A rather large deviation in the results pertaining to the aged AR-glass specimens was noted. The maximum global displacement is nearly unaffected for AR-glass but decreases for basalt due to accelerated ageing. This behaviour is indicative of a more brittle behaviour and could be caused by e.g. a reduction of the bond in the case of basalt TRC. The reinforcement ratio in all specimens is too low to induce further crack development. In future tests, the reinforcement ratio should be increased to firstly yield superior tensile behaviour for the reference case. As well, pull-out tests in combination with microscopy can be further applied to understand the degradation in bond properties due to accelerated ageing and effects of matrix densification.

Conclusions

In this study, the long-term durability in terms of alkali resistance was investigated for three types of textile reinforcement products made of carbon, basalt and AR-glass fibres. Investigations were conducted by means of exposing textile reinforcement (material level) and TRC (composite level) samples to accelerated ageing conditions. In relation to the material level, the tensile behaviour of the selected textile reinforcement products was investigated under accelerated ageing conditions as per ISO 10406-1. It was observed that the tested carbon textile reinforcement has a superior alkali and temperature resistance, while the standard conditions were found to be too aggressive for the tested basalt and AR-glass products causing them to have nearly unmeasurable capacity after ageing.

As for the composite level, after undergoing accelerated ageing and uniaxial tensile testing according to RILEM TC 232-TDT, the maximum global displacement was nearly unaffected for AR-glass but decreased for basalt TRC samples. The loss of ductility could be a sign of a reduction in bond properties between the reinforcement and the matrix. It was also noted that the exposure to high temperatures caused the first cracking load to be on average higher after accelerated ageing.

On the whole, the coating applied to the reinforcement products was found to be a governing parameter regarding the durability properties. In addition, since the tested fibres have differing degradation processes, the related durability properties could likely be better determined using adapted test methods. Further studies could involve investigation by microscopy and real-time exposure conditions.

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