APPLICABILITY OF COMPOSITE CHARPY IMPACT METHOD FOR STRAIN HARDENING TEXTILE REINFORCED CEMENTITIOUS COMPOSITES

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Abstract

Since most test methods, used for strain hardening cementitious composites, are adopted from polymer composites test standards, this paper investigates the applicability of a standard impact test (ISO 179-1:2000), which is used in the polymer composites world, on a specific textile reinforced cementitious composite using an inorganic phosphate cement (IPC) as a matrix material. The aim is to provide a test method to investigate the local impact behaviour of textile reinforced cementitious composites. It was found within this work that this method is applicable to cementitious composites provided some adaptations to the specimens' dimensions. The Charpy impact strength of an IPC matrix reinforced with different kinds of fibre types is successfully investigated. This test method can be used to qualitatively rank different cementitious composite materials.

1. INTRODUCTION

In the last few decades, many new cementitious materials were developed in order to reach thinner and stronger construction elements. The evolution started with the introduction of loose steel or polymeric fibres into the fresh concrete mixture, leading to fibre reinforced concrete (FRC): the addition of fibres into concrete provides toughness or energy absorption capacity to the inherently brittle concrete. A new generation of FRC's are the so called textile reinforced concretes (TRC) in which mainly fibre textiles (glass, polymers …) are applied as reinforcement: they can provide also a strain hardening capacity when a sufficiently high quantity of fibres is used. In a recently held conference on these kinds of materials [1], the potential of these new composites was again demonstrated. In an attempt to better define high performance fibre reinforced cementitious composites (HPFRCC), Naaman and Reinhardt [2] proposed a clear classification of these materials according to their possibility to exhibit strain hardening under bending or in tension. Within this classification a distinction is made between the four following categories: (1) crack control, (2) deflection hardening, (3) strain hardening and (4) high energy absorption.

Strain hardening cementitious composites (SHCC) not only show strain hardening under tensile loading, but also can absorb a large amount of energy. The cementitious material studied in this paper can most certainly be classified in the fourth category. It exists of an inorganic phosphate cement (IPC) matrix with different kinds of textile reinforcements. IPC was developed at the Vrije Universiteit Brussel and consists of a liquid component based on phosphoric acid solution containing inorganic metal oxides and a calcium silicate powder component. Next to the advantages of being incombustible (EN13501-1), this material also possesses a neutral pH after hardening, which allows cheap E-glass fibres to be used as reinforcement. It is however also possible to process other types of fibres, such as polymeric fibres or carbon fibres, into this cementitious matrix. Figure 1 shows typical tensile stress-strain behaviour of IPC composites with different kinds of fibre reinforcements. The fibre volume fraction is kept constant for all materials at about 20 %. It is clear from this figure that indeed all tested composite specimens can absorb a significant amount of energy due to their pronounced strain hardening behaviour after multiple matrix cracking. Note that depending on the used fibre reinforcement one can obtain a completely different composite material. For instance the curve of PE-reinforced IPC shows stiff and strong (up to 400 MPa) behaviour, while on the right side of the graph the PVA reinforced IPC shows ductile (maximum strain more than 5 %) but less strong behaviour.

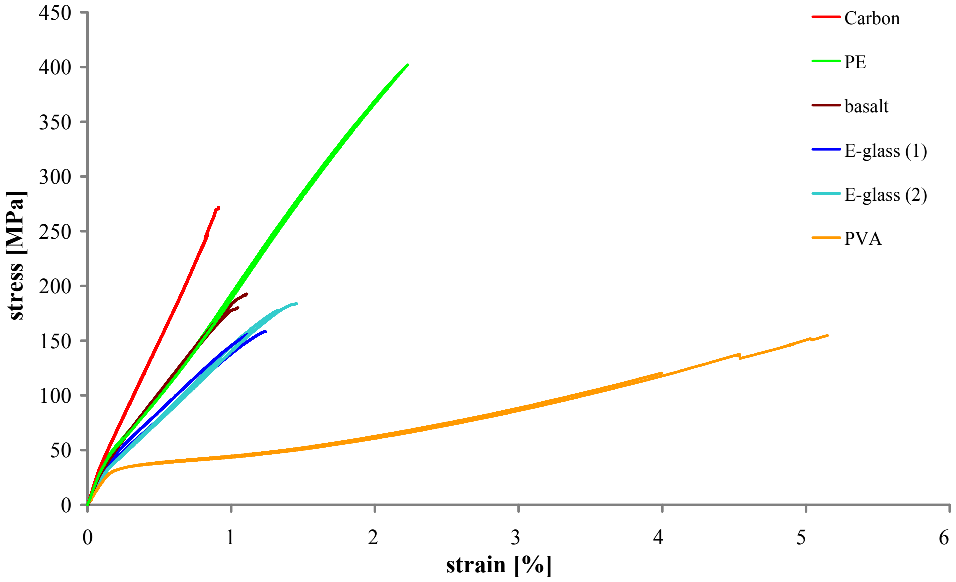

Figure 1: tensile stress-strain behaviour of IPC reinforced with different UD-fibres

This composite material has been investigated in a project that studied the possibility of producing sandwich structures that are able to absorb a significant amount of energy under blast or impact loading. The textile reinforced IPC was meant to protect the energy absorbing core against fire and to distribute the load from the explosion to the sandwich core [3]. Apparently, the material itself is able to absorb energy under blast and impact loading without failing. Under impact loading only local damage can cause failure of the material. Globally, there will be matrix cracking reducing the stiffness, but the material keeps its load bearing capacity. In this paper, the local impact damage and the corresponding energy absorption are investigated by means of impact tests.

2. CHARPY IMPACT TEST

Many test methods for SHCC – like tensile testing - are adopted from, or inspired by the polymer composites world, rather than the concrete world. Another example is the bending test: the scale of the specimen dimensions of a bending test for SHCC is much smaller than that for concrete or FRC beams. In order to study the local impact behaviour and the corresponding energy that can be absorbed, a suitable test method needs to be selected. The most common test methods concerning impact on composites are either drop weight tests or pendulum tests. In drop weight tests global and local impact behaviour can be investigated in a quantitative way. The Charpy pendulum impact test was initially designed to test the local energy absorption capacity of metals under three point bending. Adaptations of the machine's capacity and the specimen dimensions have led to the development of Charpy impact tests for other materials. In the 1980's and 1990's Charpy impact tests were developed for FRC composites [4]. The specified specimen dimensions are however not applicable for thin TRC materials. For plastics and polymer composite materials a standard test method has also been developed (ISO 179-1: Plastics – Determination of Charpy impact properties – Part 1: Non-instrumented test) [5]. It is clearly stated in this standard that the method should not be used to obtain design data. The purpose of the Charpy test is to provide a comparative test to evaluate the local impact energy absorption of different materials. The principle of the test is illustrated in figure 2 on the left. A specimen is simply supported on both sides and is impacted by a single blow of a pendulum striker. The absorbed energy is determined by calculating the difference in potential energy of the pendulum before and after impact. The reported Charpy impact strength is defined as this energy divided by the mid section area. There are different possible testing directions: the specimen can be tested flatwise or edgewise (see figure 2, right) and normal or parallel to the lamina. All specimens tested in this work are tested in normal flatwise direction. Furthermore a distinction is made between materials exhibiting interlaminar shear (ILS) and those not exhibiting this fracture mode. Similar to fracture mechanics theory the specimens can be notched. In case of cementitious composites it is however not necessary to notch the specimens since the material already contains microscopic flaws that will initiate failure. Moreover the fibres inside the material will be severely damaged by the notch.

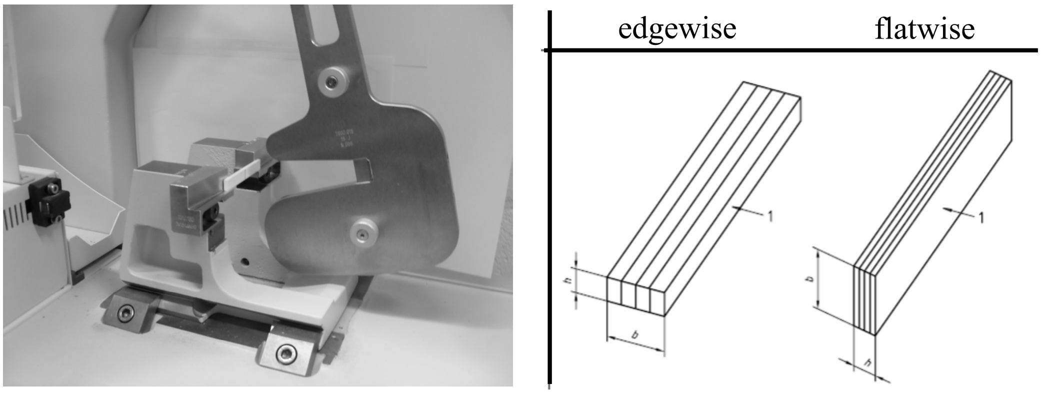

Figure 2: left: Charpy impact test; right: different test configurations [5]

The Charpy impact strength can be compared to typical values for toughness that is defined in fracture mechanics as being the energy that is necessary for the growth of a crack.

Toughness (G_c) is a material parameter, typical value for different materials can be found in Ashby and Jones [6]. For metals, values between 100 and 1000 kJ/m² are given while for most plastics the toughness is less than 10 kJ/m². Typical values for composites start at 5 kJ/m² and can reach more than 100 kJ/m².

Three specimen types are defined in ISO 179-1 [5] as illustrated in table 1. Note that the given tolerances are rather small for cementitious materials. In the experimental section the average values of the dimensions together with their standard deviation will be given. Specimen type 1 is used when the material does not show interlaminar shear. Specimen type 2 is designed to induce typical bending failure modes for materials that undergo ILS. These specimens fail in the middle section of the span either by tensile failure on the back of the specimen or compressive failure or buckling of fibres at the impacted side. The span to thickness ratio is fixed to 20 for this specimen type. To test the energy absorption capacity of interlaminar shear phenomena, specimen type 3 is designed with much smaller span to thickness ratio of 6 or 8. The value of 8 can be chosen if it is not possible for practical reasons to test at such small spans.

Table 1: Specimen types, dimensions and spans proposed by ISO-179 [5]

Specimen type	Length l (mm)	Width b (mm)	Thickness h (mm)	Span L (mm)
1	80 ± 2	10.0 ± 0.2	4.0 ± 0.2	$62^{+0.5}_{-0.0}$
2	25h	10 or 15	3	20h
3	11h or 13h			6h or 8h

3. EXPERIMENTAL STUDY

All tests in this work were performed on a Ceast Impactor II 7611 pendulum testing machine. The pendulum has a capacity of 15 J and is equipped with a processing unit that immediately calculates the Charpy impact strength. The speed at impact is 3.8 m/s. Before every series of measurements the machine is calibrated by determination of the friction in the pendulum.

3.1 2D random glass fibre mat reinforcement

The first series of specimens, which contains 2D random chopped strand glass fibre mats as reinforcement, were manufactured by hand lay-up technique [7]. The volume fraction is about 20 %. Note that only part of this fraction is contributing to the load carrying capacity of the specimen. Five different series of 20 specimens were manufactured (see table 2): the three different types of specimens according to the ISO 179-1 standard. For type 2 and 3 the influence of the width was tested (10 or 15 mm) by adding two extra series.

Table 2: Specimen dimensions of IPC reinforced with random chopped strand glass fibre mats

Specimen type	length l (mm)	span L (mm)	width b		thickness h	
			b (mm)	stdev	h (mm)	stdev
type 1	80	62	9.99	0.01	4.26	0.20
type 2 – 10	75	60	9.84	0.08	3.28	0.14
type 2 – 15	75	60	14.33	0.09	3.48	0.09
type 3 – 10	33	18	9.83	0.08	3.14	0.19
type 3 – 15	33	18	14.29	0.12	3.20	0.20

The results of these tests are made visible in figure 3 in form of boxplots. The the bold line in the middle of the grey box represents the median. Next to the boxplots, a figure shows the tested specimens and their failure modes.

In figure 3 (right) it is clear that indeed the different specimen types cause different failure types and consequently variant Charpy impact strength results. Type 1 and 2 specimens mainly fail through compression and tension (in a minor way) in the middle section. This bending failure mode is however combined with a small area of interlaminar shear for a specimen of type 1 (see figure 3), which explains the higher absorbed energy for these specimens (43.5 kJ/m²) compared to type 2 specimens (27 kJ/m²). Interlaminar shear is a failure phenomenon which absorbs more energy compared to a pure bending type of failure due to the larger free surface area that is created. Although these specimens all fail under ILS or multiple shear, there is a lot of scatter on the results of type 3 specimens. Values of almost 50 kJ/m² up to 120 kJ/m² were observed. This specimen type might therefore not be applicable for this kind of random fibre reinforced cementitious material. A possible explanation for this is that the specimen dimensions exceed the longitudinal dimension of the fibre bundles. This means that fibre bundles were cut and thus damaged during production. Finally the effect of the specimen width was investigated: mean values of specimens with a width of 15 mm seem to be slightly higher, but due to the large scatter these differences are not significant (figure 3, left).

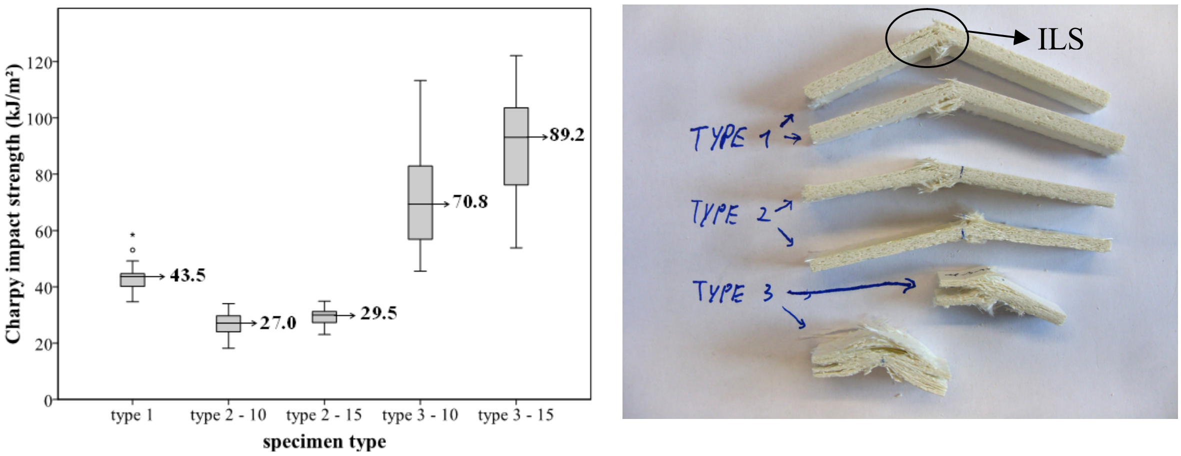

Figure 3: left: boxplots of test results, right: tested specimens, different failure types

For comparison with these results two other matrix materials are impregnated in the random fibre reinforcements. The applied matrices are a very fine grained cement mortar with a maximum grain size of 0.6 mm and an epoxy resin used in laminating applications for wind energy and boat building (EPIKOTE Resin L 135 and EPIKURE Curing Agent H 134 from Hexion). The cement mortar consists of quartz (713.6 g), quartz powder (499.5 g), cement (490.0 g), water (245.0 g), fly ash (175.0 g), silica-fume (70.0 g) and super plastifier (10.5 g).

Only results of specimens of type 1 are given, since it was found that both materials do not show interlaminar shear failure. The specimens containing mortar are too brittle causing a complete break of their middle section (figure 4, left). The average Charpy impact strength of ten impacted specimens was found to be 9.67 kJ/m² with a standard deviation of 1.84 kJ/m². The epoxy specimens on the other hand show a much larger energy absorption capacity. The average of ten tests is 93.54 kJ/m² with a standard deviation of 13.8 kJ/m². All specimens seem to fail on the tensile side of the specimens (see figure 4, right). There are two reasons for this much higher energy absorption capacity: epoxy resin has a much better bond with the fibres and shows a large strain to failure. For comparison: the elongation at break is around 0.02 % for mortar and IPC while it is 7 to 10 % for the epoxy resin. Tensile failure will occur at the back of the specimens and thus larger strain energy levels are reached. The second cause for higher energy absorption is the high flexural strength of the epoxy resin compared to the mortar or the IPC. The flexural strength of the mortar and the IPC is about 10 MPa while that of the epoxy resin is 110 to 130 MPa. Although the energy absorption of the IPC specimen is smaller than that of polymer composite materials, it absorbs more energy than can be derived from the properties of the matrix material itself.

Figure 4: impacted specimens with mortar matrix (left) and epoxy matrix (right)

3.2 Unidirectional reinforcement

The aim of this section is to validate this standard test method for IPC specimens with different kinds of fibre types as reinforcement. In order to be comparable the specimens should contain the same amount of fibres. The fibre volume fraction (approximately 20 %) could be well controlled by using a self-made pultrusion set-up to impregnate the fibre bundles. Once impregnated, the bundles were put straight in a mould which is pressed together. Specimens are then cured for 24h at room temperature and post-cured for another 24h at 60°C. The different fibre types with their properties can be found in table 3. Glass fibre rovings are manufactured by Owens Corning, basalt fibres are from Basaltex, carbon from TOHO, PVA from Nordifa and PE from DSM.

Table 3: different fibre types with their properties

fibre type	**density** (kg/m³)	**tex** (g/km)	**strength** (MPa)	**stiffness** (GPa)
glass SE-1200[1]	2600	600	950	75
glass SE-1500[2]	2600	600	950	75
basalt	2700	1600	1100	78
carbon	1800	250	1275	170
PVA	1300	250	1000	33
PE	975	176	1870	105

[1] straight fibre bundles, [2] twisted fibre bundles

Since specimens made with IPC and UD glass fibres, all showed ILS, it was decided to test both specimen types 2 and 3 for all fibre types. The first series of tests are type 2 tests with nominal dimensions of 10mm x 3mm x 75mm with a span of 60 mm. Specimens were however, due to manufacturing, averagely 3.3 mm thick, which lowered the span to thickness ratio to 18 in stead of 20. In more than 65 % of the tested specimens, interlaminar shear was observed (figure 5). This is probably due to the relative weak bond between fibres and matrix.

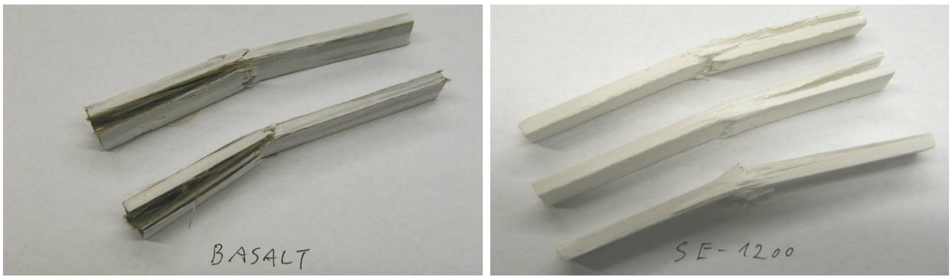

Figure 5: observed ILS failure in type 2 specimens

To tackle this problem the following solution was found: to encourage a bending type of failure, the ratio span to thickness should be increased. This was obtained by decreasing the nominal thickness of the specimens to 2 mm, while the span is kept constant at 60 mm. The theoretical span to thickness ratio now becomes 60/2 = 30. The manufactured specimens for this series had an average thickness of 2.2 mm, which lowers this ratio to 27.3. These adapted specimens all failed in the middle section under bending. The obtained values for the Charpy impact strength are shown in Figure 6 (left). Due to scatter, the differences between the median values are not significant except for the glass fibres SE-1200. This could be expected from visual inspection of the tested specimens. All specimens failed under bending at the compressive side of the specimen, which is more related to the matrix material than to the used fibre reinforcement. In order to increase the energy absorption of these materials the bond between fibres and matrix should be increased. Local reinforcement at the impact point can also improve the performance of these materials.

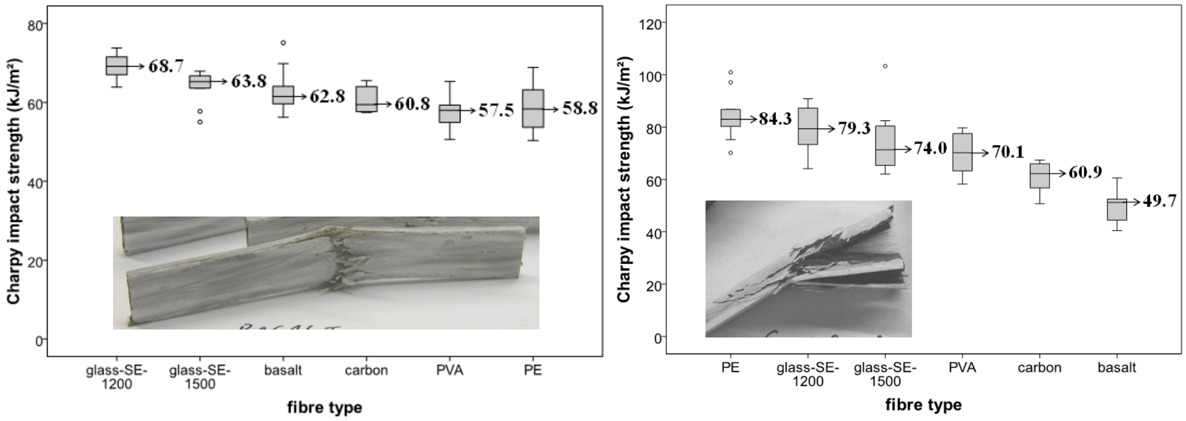

Figure 6: results of adapted specimens of type 2 (left) and specimens of type 3 (right)

The last series of tests are performed on type 3 specimens. The average thickness of the specimens is around 3.3 mm with a standard deviation of 0.1 mm. This results in a specimen length of 43 mm and a span of 26.4 mm according to table 1. The results are shown in the right hand graph of figure 6. The specimens all failed under ILS as can be seen in the example in figure 6 (right). In this study the specific used polymer and glass fibres absorb more energy under ILS than the carbon and basalt fibres. This can be linked to the bond quality between the fibres and the matrix. The basalt fibres seem to be less well impregnated than all other fibre types.

4. CONCLUSIONS

Since most test methods, used for strain hardening cementitious composites, are adopted from polymer composites test standards, it was suggested within this paper to investigate the applicability of a standard impact test from the polymer composites world on these materials. The aim is to provide a test method to investigate the local impact behaviour of cementitious composites. The following conclusions can be drawn:

- The proposed test method can indeed be applied for qualitative comparison of the local impact resistance and energy absorption capacity between different strain hardening TRC materials.
- Due to the poor fibre-matrix bond, interlaminar shear becomes an important damage mechanism.
- Specimens of type 2 should be thin enough (span to depth ratio above 30) to avoid interlaminar shear effects

In order to be able not only to rank different materials, but also to be able to investigate their local impact behaviour in detail, instrumented Charpy impact tests can be performed. In future work this possibility will be explored in order to be able to quantify the damage and to compare these results with more global impact tests like drop weight tests.

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