HYBRID CEMENT-BASED COMPOSITES: DYNAMIC AND STATIC TENSILE BEHAVIOURS

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Summary: Hybrid systems with two or more fiber materials are used to combine the benefits of each fiber into a single composite product. Textile fabrics technology enables several ways to combine two or more yarn materials within a single fabric, with controlled orientation and location of each material either in orthogonal or co-linear directions. Textile reinforced cement-based composites (TRC) was found to highly improve performance of cement-based elements under low and high strain rate loading. Combining the advantages of textiles with hybrid composition can lead to superior performance of cement-based products, controlling the desired properties in the exact directions of the element following the magnitude and the direction of loading of the specific application. The purpose of the current work was to study the tensile behavior under dynamic and static conditions of cement-based composites reinforced with hybrid fabrics. Hybrid fabric composites made of different content of brittle/ductile yarns were developed and studied with the following ratios: 1:0, 3:1, 1:1, 1:3, and 0:1. It was found that combination of PP and glass yarns in a hybrid fabric, highly influence the tensile behavior of cement-based composites, under static condition. Different hybrid ratios can lead to a range of properties from brittle composite to high ductile composite with very high strains. However, under dynamic loading no significant benefit of PP-glass hybrid composition was observed, all hybrid composites showed similar brittle behavior. A good correlation was found between fabric properties and composite behavior, for both loading rates.

1 INTRODUCTION

There is an increased interest for using textile fabrics as reinforcement for concrete (TRC). TRC elements found to improve tensile strength, strain capacities (e.g. strain hardening) and enables high-energy absorption up to failure [1-2]. The properties of TRC elements are highly dependent on the reinforcing material. For example, brittle materials such as AR glass (Alkali Resistant glass) tend to suffer from durability problems but provide composites with high stiffness and strength, while hydro-
phobic polymeric materials such as polypropylene suffer from low bonding with the cement matrix but allow composites with ductile behavior and improved energy absorption.

Composites with optimal performance can be produced by combining different materials in hybrid formation [3-8]. In hybrid systems, two or more fiber materials are used to combine the benefits of each fiber into a single composite, providing a composite that is both strong and tough as compared to mono fiber type composite. Earlier data showed that in hybrid system composed by AR glass and polypropylene (PP) the hybrid composite found to be stronger than a mono PP yarn composite and tougher than a mono AR glass yarn composite [3]. This combination of the two materials has great interest due to their extreme differences in properties and behavior. AR glass composites show good bonding with the cement matrix, high tensile modulus, brittleness, low toughness (energy to failure), durability problems and vulnerability to corrosion, whereas PP composites show opposed properties to that of the AR glass system. Few approaches of using hybrid combinations were investigated. Most common one is combining short fibers, randomly dispersed in the cement-based composite [3-7]. In these cases there is a limitation on controlling the exact location of the fibers within the composite, which can be significantly important for many applications. Another way can be by using different layers of different fabrics in a single composite. The production of the hybrid composite using this method is relatively easy, however the produced composite has different properties, depends on the reinforcing material in each zone. This approach shows high advantage of improving the composite mechanical properties, but its main drawback is delamination, which occurs between different zones having different tensile modulus and bond strength, i.e., each zone performs separately which can be problematic from a structural point of view [8].

Modern textile technology offers several ways to combine two or more yarn materials within a single fabric, i.e., production of hybrid fabrics, which can allow full control on the exact location of each yarn and its orientation in the composite during production. Combining the advantages of textiles as reinforcement with hybrid fabric composition can lead to superior performance of cement-based products, controlling the desired properties in the exact direction of the element following the magnitude and the direction of loading of the specific application. When dealing with fabric reinforcement for cementitious matrices, it is preferred that the fabric will be with an open structure that will allow good matrix penetrability in between its opening. One common fabric structure that enables open structure along with hybrid combination of different yarn materials, is the warp knitted technology. In this fabric type each yarn can be formed by a different material, where two sets of straight yarns are connect together by stitches along the two directions of the fabric (weft and warp), providing an open structure. Thus, this kind of reinforcing fabric was chosen for the current work.

The purpose of this work was to study the dynamic and static tensile behavior of cement-based composites reinforced with hybrid fabrics made of different content of brittle/ductile yarns as follows: 100:0, 75:25, 50:50, 25:75, 0:100%. All the composites were made out of four layers of fabric in a cement paste made of 0.4 water cement ratio prepared with the pultrusion technique. Correlation between the static and dynamic tensile properties of the composites as well as between fabrics and composites were investigated.

2 EXPERIMENTAL PROGRAM

2.1 Fabrics

Hybrid warp knitted fabrics were examined, in which AR glass yarns and PP yarns were combined in a single fabric, located along the longitudinal direction of the fabric (warp direction), with repetitive structure each include four yarns [Figure 1]. Different hybrid combinations of the AR glass-PP yarns were investigated with yarns ratios of: 100:0, 75:25, 50:50, 25:75, 0:100%, glass(G):PP(P) respectively, providing five different types of fabrics. The fabrics and the related composites will refer here as follows: 100G, 75G25P, 50G50P, 25G75P and 100P. In order to achieve such yarn ratios, four warp yarns were alternated within the fabric, having the formation of: G-G-G-G, G-G-G-P, G-P-G-P, G-P-P-P, P-P-P-P. For example, the 50G50P having a repetitive structure with one yarn of glass followed by
one yarn of PP, one yarn of Glass and one yarn of PP – this define one repetitive cycle of four yarns in the fabric.

The AR glass yarns were with a 1200 tex and the PP with 444 tex. In all fabrics, the weft yarns (perpendicular to the loading direction) were AR glass with 1200 tex. The stitches connected the yarns together to a fabric form were of polyester with 16.7 tex. The reinforcing (warp) yarns were inserted in a two in two out formation, e.g., two yarns are as a pair and then two empty spaces, alternately. The weft yarns were inserted in a one in one out formation. Both warp and weft yarns were made from multifilament bundle.

![Reinforcing direction](image)

**Figure 1:** One repetitive cycle of the hybrid fabric structure.

### 2.2 Composites preparation

The pultrusion technique [9] was used to produce the composites, due to its ability to increase penetrability of the cement paste in between the fabric openings. This can increase the reinforcing efficiency of the fabrics; hence, the difference between the two yarn materials assemble the hybrid fabric can be more significant. A cement paste was used for the matrix (cement and water only), with a water/cement ratio of 0.4, as it provides proper rheology for the pultrusion manufacture technique. Laminated thin sheet composites with four layers of fabrics were produced with dimension of 30X30X0.8cm lengthXwidthXthickness for each system. For the static tensile testing, each sheet was cut to slices of 25X3X0.8cm lengthXwidthXthickness. For the dynamic tensile testing, each sheet was cut to slices of 16X3X0.8cm lengthXwidthXthickness in order to fit the sample dimension to that of the testing equipment. The yarns content of the different composites are listed in Table 1.

The curing process consist of 1d of hardening after casting, then cutting the composite board, 3d in water bath at room temperature, 7d in 100%RH (Relative Humidity) at 50 °C and another 3d in 60%RH and room temperature. This curing process represents the composite behavior after long aging period.

<table>
<thead>
<tr>
<th>Composite composition [%P]</th>
<th>0</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume fraction in tensile direction [%]</td>
<td>0</td>
<td>2.2</td>
<td>1.43</td>
<td>2.19</td>
<td>3.02</td>
</tr>
<tr>
<td>PP volume fraction</td>
<td>9</td>
<td>2.06</td>
<td>1.31</td>
<td>0.67</td>
<td>0</td>
</tr>
<tr>
<td>Glass volume fraction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume fraction in transverse direction Glass [%]</td>
<td>1.49</td>
<td>1.74</td>
<td>1.66</td>
<td>1.71</td>
<td>1.74</td>
</tr>
</tbody>
</table>

Table 1: Average yarns volume fraction in the tensile and transverse direction of the composite samples.
2.3 Mechanical Testing

All fabrics and composites were tested in static tension with a close loop tensile machine. Both fabrics and composites were tested at the same rate of 0.5mm/min (although fabrics can withstand higher loading rates), in order to keep the same loading conditions and to enable comparison of fabric and composite behavior. For each system, 6 samples were tested. One representative sample was chosen from each system for comparison, based on average typical behavior. In the case of the fabric, only one layer of fabric was tested having four yarns along the loading direction (one repeat unit of the hybrid). Each sample was gripped 5 cm from each side, leaving a 15cm free length for testing. The same procedure was carried out for the dynamic tension test, using a MTS high rate servo-hydraulic testing machine, which can operate in closed-loop and open-loop at a maximum speed of 14 m/s with a load capacity of 25 kN [10]. Once a trigger is pushed, an actuator is accelerates up to constant speed of 1150 mm/sec, then the sample locked on the grips and the force transferred to the sample. The actual speed operating on the sample is about 500 mm/sec. Each sample was gripped 5cm from each side, leaving a 6 cm free length for testing.

During tensile testing the propagation and development of cracks was captured by a camera for crack pattern investigation in both loading rates. The camera was set to take an image every 10 seconds for the static tensile testing, and a video sequence with 10,000 images every second for the dynamic test (using a Phantom v.7 high speed digital camera).

Stress-strain curves were calculated. Based on these curves the average maximum tensile stress and toughness (area under stress-strain curve) were calculated for each sample as well as the maximum strain.

3 RESULTS AND DISCUSSION

3.1 Fabric behavior

The overall tensile behavior of the different hybrid fabrics (without cement) under low and high speed tensile loadings is presented in Figure 2. The ultimate strength (Max Stress), strain and toughness (as the area under the stress-strain curves) were calculated [Table 2]. All results in the table are referred to the maximum stress obtained for each fabric type.

Table 2: Static and dynamic tensile properties of the hybrid fabrics (without cement), function of the PP yarn content (%P) at the maximum stress values.

<table>
<thead>
<tr>
<th>Loading rate</th>
<th>%PP Property</th>
<th>0</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength [MPa]</td>
<td>627</td>
<td>579</td>
<td>389</td>
<td>322</td>
<td>397</td>
</tr>
<tr>
<td>Static condition</td>
<td>(46)</td>
<td>(49)</td>
<td>(78)</td>
<td>(11)</td>
<td>(5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Toughness [J/cc]</td>
<td>6.20</td>
<td>7.32</td>
<td>5.37</td>
<td>66.24</td>
<td>77.71</td>
</tr>
<tr>
<td></td>
<td>(1.00)</td>
<td>(1.73)</td>
<td>(1.82)</td>
<td>(3.69)</td>
<td>(8.96)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strain [%]</td>
<td>1.89</td>
<td>2.31</td>
<td>2.35</td>
<td>30.67</td>
<td>30.07</td>
</tr>
<tr>
<td></td>
<td>(0.27)</td>
<td>(0.46)</td>
<td>(0.47)</td>
<td>(1.64)</td>
<td>(3.01)</td>
<td></td>
</tr>
<tr>
<td>Dynamic condition</td>
<td>Strength [MPa]</td>
<td>277</td>
<td>246</td>
<td>193</td>
<td>133</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>(59)</td>
<td>(49)</td>
<td>(48)</td>
<td>(17)</td>
<td>(24)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Toughness [J/cc]</td>
<td>1.32</td>
<td>1.71</td>
<td>0.83</td>
<td>0.85</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>(0.23)</td>
<td>(0.67)</td>
<td>(0.35)</td>
<td>(0.21)</td>
<td>(1.12)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strain [%]</td>
<td>0.85</td>
<td>1.21</td>
<td>0.75</td>
<td>1.12</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>(0.14)</td>
<td>(0.35)</td>
<td>(0.27)</td>
<td>(0.26)</td>
<td>(0.03)</td>
<td></td>
</tr>
</tbody>
</table>

* The values in brackets are the standard deviations.
Figure 2: Tensile behavior of the hybrid fabrics (without cement): (a) static condition, (b) dynamic condition, large scale as the static behavior, and (c) low scale.

At both tensile loading rates, the mono AR glass fabric (100% glass yarns) shows the highest stress capacity [Figure 2 and Table 2]. Comparison between the mono fabrics 100% glass and 100% PP shows differences in properties. Most significant is the change in ductility of the mono PP fabric at the two loading rates. Under high speed loading, its behavior is much more brittle as compared to extremely higher ductility under static loading, 0.88% compared to 60% strains at failure under dynamic and static conditions, respectively. The difference due to increased strain rate in the glass fabric is less, 1.89% and 0.85% under low and high speeds, respectively, but also here the high speed loading increases brittleness. In addition, the tensile strengths are different between low and high speed loading tests, the high speed condition causes reduction in strengths. For the glass fabric, the strengths are of 627MPa and 277MPa for static and dynamic conditions, respectively, which means that the high speed tensile strength is 56% lower than the static tensile strength. Whereas, for the PP fabric the strengths are of 397 MPa and 126 MPa for the low and high speed, respectively, which means that the high speed tensile strength is 68% lower than the high speed tensile strength. Thus, the endurance of the PP fibers under dynamic loading is less than the endurance of the glass fibers under dynamic loading. When comparing the ability of each fabric to withstand stresses, it can be seen under static
loading that the PP fabric has 37% less strength than the glass fabric under static loading, and under dynamic loading the PP fabric strength is 55% less than the glass fabric strength under dynamic loading. Hence, not only that the PP fibers are less strong compared to the glass fibers, it also more sensitive to the loading rate.

The tensile behavior of the hybrid fabrics is more complex, especially under static loading. At the static condition the hybrid fabrics exhibit two peaks, the first is at low strain similar to that of the mono (100%) AR glass fabric and the second is at much larger strain similar to that of the mono PP fabric (Fig. 1a). It appears that the first peak increased with increase of the glass yarns content, while the second peak increases with greater content of the PP yarns within the hybrid fabric. This indicates that AR glass yarns govern the first peak of the hybrid fabric, and the second peak is governed by the PP yarns, under low speed loading. The ratio between these two peaks, i.e., which peak is higher, depends on the content of each yarn types within the hybrid fabric, whether more yarns are glass or PP.

Under dynamic condition, no such double peak behavior is observed (Figs. 1b, 1c). Here both PP and glass fabrics behave in a brittle manner and they tend to fail at similar strains, therefore only one peak is observed. Note that the behavior of these fabrics is presented in large strain scale (Fig. 1b), to enable comparison with the static behavior, and low strain scale (Fig. 1c) to observe the fabrics behavior in details under the high speed rate loading. In both cases, only one peak is observed, i.e., the PP yarns do not contribute as they do under low speed loading. In static condition the PP yarns behave very ductile as compared to the brittle behavior of the glass yarns therefore they lead to the two peaks discussed above.

Figure 3 shows the change in the average strength, toughness and strain to maximum stress of the different fabrics under low speed (Figure 3a) and under high speed (Figure 3b). Note that in the case of the static condition the presented maximum stress is the stress of the first or second peak, depending either the highest stress is govern by glass or by PP yarns.

![Figure 3](image)

**Figure 3:** The change of stress, strain and toughness in the hybrid fabrics at maximum stress value, as a function of the PP yarns content: (a) static condition (b) dynamic condition.

Reduction in fabric strength is seen when the PP yarns content increases for both loading rates, up to a certain content. When toughness is considered, the situation is different. At static loading, up to PP content of 50%, hardly any change in toughness is observed, however when the PP content reaches 50% a significant increase is seen up to 75% PP with further improvement in toughness up to 100% PP. This correlates well with the change in strain at maximum stress. These trends indicate that the glass yarns are controlling the fabric properties up to a content of about 50%, whereas the PP contributes from about 50% PP and above, under static condition. It appears that the main change in the hybrid fabric properties is somewhere between 50% to 75% of PP yarns of the fabric exposed to
low rate loading condition. For the dynamic loading the situation is quite different, no significant difference in toughness and strain is observed when the PP content increases within the fabric. This means that under dynamic loading the contribution of the PP and glass yarns is similar on strain and toughness.

It may conclude that under low speed condition a proper ratio between glass and PP yarns within the hybrid fabric will be somewhere between 50% to 75% of PP to allow similar contribution of glass and PP to the overall stress behavior of the fabric. However, under high speed loading there is no significant change in toughness or strain whether glass or PP yarns are dominant, as the PP yarns behave in a brittle manner similar to the behavior of the glass yarns. In the case of strength, glass are stronger in both loading rates and therefore the hybrid fabric is stronger where the content of the glass yarns is increased.

3.2 Composite behavior

3.2.1 Repeatability consideration

Table 3 presents the average stresses, toughness and strains of all tested composites at maximum stress, tested under high and low speed rates.

<table>
<thead>
<tr>
<th>Tensile method</th>
<th>%PP Property</th>
<th>0</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength [MPa]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static condition</td>
<td>6.63 (1.06)</td>
<td>7.09 (1.67)</td>
<td>5.44 (0.52)</td>
<td>7.74 (1.31)</td>
<td>12.80 (1.27)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Toughness [J/cc]</td>
<td>0.023 (0.008)</td>
<td>0.023 (0.007)</td>
<td>0.032 (0.032)</td>
<td>0.764 (0.123)</td>
<td>1.084 (0.107)</td>
</tr>
<tr>
<td></td>
<td>Strain [%]</td>
<td>0.60 (0.10)</td>
<td>0.55 (0.09)</td>
<td>0.84 (0.60)</td>
<td>15.27 (0.90)</td>
<td>13.29 (0.05)</td>
</tr>
<tr>
<td>Dynamic condition</td>
<td>Strength [MPa]</td>
<td>3.00 (0.85)</td>
<td>5.29 (0.35)</td>
<td>5.21 (0.67)</td>
<td>4.67 (1.05)</td>
<td>5.58 (1.23)</td>
</tr>
<tr>
<td></td>
<td>Toughness [J/cc]</td>
<td>0.013 (0.005)</td>
<td>0.037 (0.008)</td>
<td>0.042 (0.015)</td>
<td>0.032 (0.006)</td>
<td>0.037 (0.005)</td>
</tr>
<tr>
<td></td>
<td>Strain [%]</td>
<td>0.77 (0.26)</td>
<td>1.23 (0.34)</td>
<td>1.29 (0.43)</td>
<td>1.26 (0.47)</td>
<td>1.24 (0.61)</td>
</tr>
</tbody>
</table>

* The values in brackets are the standard deviations.

Figures 4a&b shows the static and dynamic tensile behavior of all tested specimens for mono glass composite system (100G). The system tested under static condition exhibits very good repeatability observing relatively low scattering of the stress-strain responses for the different tested specimens (Figure 4a), i.e., good uniformity with low standard deviations (Table 3). On the other hand, the behavior under dynamic tensile loading shows poor repeatability with high difference between the stress-strain responses of the different samples (Figure 4b). The repeatability behavior under static loading is valid at low strains as well as at the post peak behavior. This is very different than the responses under dynamic loading, as scattering is observed through the entire testing, with significant differences in stresses and toughness. This means that while the composite tested under static condition can be predicted with high precision, it is not easy to predict the dynamic behavior of the same composite system. A higher safety factor should be considered when those composites are expected to expose
to dynamic loads than to static loads. Note that similar trend was obtained with the mono PP fabric composites, good repeatability behavior under static loading and high spreading of behavior under dynamic loading.

When looking at a tensile behavior of the hybrid composites, i.e., the 50P50G system under static condition (Figure 4c), it is possible to see that up to the first peak the stress-strain responses are relatively uniform with good repeatability. However, at the post peak region the situation is different and much less consistency in behavior is observed. This situation is opposed to the good repeatability in tensile behavior of the mono glass composites discussed above under static loading. This suggests that the hybrid system due to its complexity lead to less consistency in the total behavior of the composite when subjected to static loading. However, the hybrid system under dynamic loading exhibits better repeatability in tensile behavior (Figure 4d) than that tested for the mono glass composites under dynamic condition (Figure 4b). These trends were observed for all tested hybrid composites. These behaviors have high importance in terms of structure safety.

Figure 4: The static (a) and the dynamic (b) tensile behavior of the 100G system, the static (c) and dynamic (d) tensile behavior of the 50P50G system, for all tested composites at these systems.
3.2.2 Overall behavior

A comparison of the overall tensile behavior for all tested composite systems with different PP-G contents is presented in Figure 5.

![Figure 5: The composites tensile stress-strain behavior.](image)

When comparing the overall static behavior of the composites up to failure [Figure 5a] it observed that the maximum strain at composite failure varies significantly between the different tested systems. For the 100P and 75P25G static systems, the composite strain at failure is very high, reaching value of about 14%. However, when the PP content is reduced to 50% and below the strain at failure is much lower, with less than 5%. This correlates well with the fabric properties where the highest stress values of the 75% PP and 100% PP fabrics are obtained at the second peak [Figure 2a], e.g., the fabric strength controlled by the PP yarns. This suggests that above this PP content (between 50% to 75%) the PP yarns control the composite behavior leading to high ductile composite. Below this content, the composite response is mainly controlled by the glass yarns, leading to much more brittle behavior of the composite.

In contrary to the static behavior, under high speed loading tests there is no significant differences between the hybrid systems and mono PP, i.e., those containing PP yarns in all contents [Figure 5b, Table 3]. In all four composite systems, the stress-strain response is quite the same. The mono glass fabric composite exhibits relatively low tensile stresses and more brittle behavior as compared to the hybrid and mono PP systems. That means the glass yarns has small influence on the ability of the composite to carry loads under high speed rate loading.

Figure 6 presents the maximum stress values, toughness and strain up to maximum stress, under static and dynamic conditions. As for the static behavior, an increase in composite toughness is observed when the PP content reaches 50% and up [Figure 6a]. Similar trend is observed for the strain and the strength values. As for the composite toughness and strain, it behaves similar to the behavior of the fabrics [Figure 3a], e.g., dramatic increases in toughness and strain from 50% PP content and up, and no change below this content. This suggests that under static conditions the toughness of the composites mainly influenced by the fabric properties. However, when comparing the tensile strength properties of the fabrics and composites almost a mirror behavior is seen between these two systems. While the fabrics tend to have higher strength with higher AR glass fiber content, the composites tend to have lower strength with higher AR glass yarns content. It is important to notice that the curing applied in the current work represents long aging period (7 days in hot bath). Such curing condition and
aging may cause some durability problems of the glass fabrics due to corrosion, while the PP fabrics are less affected.

![Figure 6: Strength (Max Stress), toughness and strain at the maximum stress value, as a function of PP yarns content, under static loading (a) and dynamic loading (b).](image)

On the contrary, the composites tested under dynamic loading show no significant change of the toughness and the strain capacities as the PP content increases [Figure 6b]. This behavior correlates well with fabric behavior discussed above [Figure 3b]. Also under dynamic loading, the change in composite strength as the PP yarn content increases is also opposite to that of the fabrics, similar to the trend seen under static condition, i.e., greater glass yarns content lead to higher strength of the fabric, but lower strength of the composite. This is most likely due to durability effects on glass yarns.

These results clearly indicate that under static condition the PP yarns highly contribute to the overall behavior of the composite, greater content of PP yarns leads to higher toughness, strain and strength of the composites. However under dynamic condition the amount of the PP yarns do not highly influence the composite performance, all composites even with high amount of PP yarns perform more or less similar. This means that under dynamic loading the benefit of hybrid combination becomes less significant.

3.3 Cracking Patterns

The crack pattern observed in Figures 7 and 8, for the different composite systems under static and dynamic loadings, respectively. The images were taken when the composite reached its maximum tensile stress, for representative sample from each tested system. Multiple cracking behavior is observed for all composite systems under both loading rates. However, the crack width, number of cracks and the cracks distribution is quite different depending on the hybrid content. For 100G composites, the cracks are extremely small and can hardly seen by naked eyes, this until one crack becomes the major crack and widen up to failure. This behavior is seen for both static [Figure 7a] and dynamic systems [Figure 8a]. When increasing the amount of PP yarns in the hybrid composites, the cracks become more visible and wide [Figures 7b-d, 8b-d] and the number of cracks becomes higher. For the 75P and 100P composites, the cracks can be easily recognized under both testing rates [Figure 7d-e and 8d-e]. This may suggest that the cracks are mainly widening due to the presence of the PP yarns, as the PP yarns are pulling out when loads are increased. Therefore, as more PP yarns are present within the composites, cracks widening becomes the dominant mechanism. Such mechanism expected to lead to larger strains, which is the case under static condition. However, under dynamic condition the strain are very low even when high content of PP yarns are employed, but still widening
of the cracks is clearly observed. Moreover, there is no significant difference in tensile response whether the content of the PP yarns is 25% or 100% under high speed loading, but the width and distribution of the cracks increases with increased content of PP yarns. These results are quite interesting and important when discussing the mechanisms controlled composites behavior under static and dynamic conditions. These behaviors need to be further investigated and analyzed. When looking more deeply at the width of the cracks when high content of PP yarns are used, it may suggested that the average cracks width is less under dynamic condition than under static condition. This needs better quantitate analysis, but may partly results the low strains obtained under dynamic behavior.

Figure 7: The cracking patterns of the different composite systems, at strain of maximum stress, under static tensile behavior.

Figure 8: The cracking patterns of the different composite systems, at the strain of maximum stress, under dynamic tensile behavior.
4 CONCLUSIONS

Hybrid fabric combination of PP and glass yarns was investigated. The hybrid fabrics highly influence the tensile behavior of cement-based composites, under static condition. Different hybrid ratios can lead to a range of properties from brittle composite to high ductile composite with very high strains. However, under dynamic loading no significant benefit of PP glass hybrid composition was observed. Increase in the loading rate results in brittleness of the composites, as well as reduction in their strength.

A good correlation was found between fabric properties and composite behavior, for both loading rates. Under static condition the glass yarns mainly influence initial properties of the composite (at low strain) where the PP yarns mainly govern the final properties of the composite (high strain), especially its ductility. Under dynamic condition, the fabrics were brittle whether glass or PP were involved, leading to brittle composites.

The properties of the fabric under static condition were highly depended by the hybrid content. The stress-strain behavior of the hybrid fabrics observed two stress peaks, the first was controlled by the glass yarns while the second was governed by the PP yarns. Above 50% PP the second peak was higher and below this PP content the first peak was the greatest. Under high speed loading only one peak was observed and the fabric strength was determined by the stronger material, i.e., the PP yarns.

Integration of hybrid fabrics in cementitious composites allows controlling composite properties such as strength, toughness and ductility for the specific element requirements with the best reinforcement efficiency, enables gaining the maximum of each fiber type.

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