Hybrid Fabrics as Cement Matrix Reinforcement

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Summary: Hybrid systems with two or more fiber materials were used to combine the benefits of each fiber into a single composite product. Strength and toughness optimization of hybrid thin sheet composites has been studied extensively using combination of different fiber types with low and high modulus of elasticity. Hybrid reinforcement is more significant when the reinforcing structure is in fabric geometry. Fabric structure provides full control on the exact location of each yarn and its orientation in the composite during production, thus maximizes the reinforcing efficiency. A high-strength, high-modulus fiber primarily tends to increase the composite strength with nominal improvements in toughness. A low-modulus fiber expected to mainly improve toughness and ductility. Combination of two or more types of fiber can produce a composite that is both strong and tough as compared to a mono fiber composite. The purpose of the current work was to study hybrid warp knitted fabrics as reinforcement for cement-based composite, having AR (Alkali Resistance) glass and Polypropylene (PP) as the reinforcing yarns. The examined ratios between the two different yarns were 0:100, 25:75, 50:50, 75:25, 100:0 (glass: PP, by percentage). It was found that in the hybrid system, the fracture mechanism is a superposition of the mono systems, and the tensile behavior is a combination between the two materials.

1 Introduction

Recently there is an increase interest in the use of Textile Reinforced Concrete (TRC) due to their enhanced mechanical behavior. TRC elements found to enhance tensile strength, strain capacities (i.e. strain hardening) and high-energy absorption to failure [1-2]. Although those composites have apparently good properties, the properties depended highly on the reinforcing material. As there are advantages and disadvantages of each reinforcing material, an ap-

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proach of combining different materials in hybrid formation was suggested [3-8]. Earlier data showed that in hybrid system made by AR glass and PP fibers the fracture of the AR glass filaments was more evenly distributed than in the single AR glass composite, leading to greater strains at maximum stress of the hybrid composite. In addition, hybrid composite with AR glass and PP yarns were found to be stronger than a mono PP yarn composite and tougher than a mono AR glass yarn composite. This combination of the two materials has great interest due to the extreme differences in their properties and behavior. AR glass yarns show good bonding with the cement matrix, high tensile modulus, brittleness, low toughness (energy to failure), durability problems and vulnerability to corrosion, whereas PP yarns show opposed properties to those of the AR glass yarns.

The main approach of investigating hybrid reinforcement was by using different layers of different fabrics [8]. With this method it was easy to produce the composite but it resulted in different zones within the composite, depending on layer material location. These hybrid composites showed high enhancement in mechanical properties, but delamination was developed between the different fabric layers having different properties and bond strengths, i.e. they performed separately, and hence did not operate one another.

Textile technology enables to manufacture fabrics that contain two or more different yarn materials in a single fabric. One common fabric structure that enables such hybrid combination is the warp knitted fabric. In this fabric type, the yarns are connected together by stitches providing relatively straight yarns along the two directions of the fabric (weft and warp) as well as open structure. Thus, such kind of reinforcing fabric was chosen for the current work.

The main goal of the current work was to study hybrid warp knitted fabrics as reinforcement of cement-based composites, made of two yarn types with significant different properties: AR (Alkali Resistance) glass and Polypropylene (PP) with various content combinations. This was to optimize yarn material combinations to tailor fabric design to the specific needs of different cement-based composite products, taking into consideration the particular application, the anticipated loading magnitude and the loading type (static, dynamic or impact). Each application requires different characteristic such as: strength, energy absorption, ductility, long-term durability (corrosion), and cost. In this paper tensile static properties of AR glass-PP hybrid composites are presented.

2 Materials and Testing

2.1 Fabrics

Hybrid warp knitting 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). Different hybrid combinations of the AR glass-PP yarns were investigated with yarn ratios of: 100:0, 75:25, 50:50, 25:75, 0:100%, glass (G):PP(P) respectively, providing five different fabrics. The fabrics and the related composites will refer here as follow: 100G, 75G25P, 50G50P, 25G75P and 100P. In order to achieve such yarn ratios, four warp yarns were alternating 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. 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 to a fabric form were PP with 16.7 tex. The reinforcing (warp) yarns were inserted in a two in two out formation, i.e., 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.

2.2 Composites preparation

The pultrusion technique [10] was used to produce the composites due to its ability to increase the reinforcing efficiency of the fabrics; hence, the difference between the two yarn materials can be more significant. A cement paste was used for the matrix (cement and water only), with a water/cement ratio of 0.4. The water/cement ratio determined so that it will have the proper rheology for the pultrusion manufacture technique. Laminated thin sheet composites with four layers of fabrics were produced with dimension of 30X30X0.8 cm lengthXwidthXthickness for each system. Each sheet was cut to slices of 25X3X0.8 cm lengthXwidthXthickness. The curing producer was as follows: 1 d of hardening after production, cutting the composite board, 3 d in water bath at room temperature, 7 d in 100% RH (Relative Humidity) at accelerated temperature of 50^0C and another 3d in 60% RH at room temperature.

2.3 Mechanical Testing

Both fabrics and composites were tested in 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 to enable comparison of fabric and composite behaviors. For each system 6 samples were tested. One representative sample was chosen from each system for comparison. In the case of the fabric one layer of fabric was tested having four yarns along the loading direction (one repeat unit of the hybrid). Tensile stresses and toughness (area under stress-strain curve) were calculated for fabrics and composites.

During tensile testing the propagation and development of cracks was captured by a camera to investigate crack pattern. The camera was set to take an image every 10 seconds.

3 Results and Discussion

3.1 Fabric behavior

3.1.1 Overall behavior

The overall tensile behavior of the different hybrid fabrics is presented in Figure 1. The average ultimate strength, strain and toughness and standard deviations of all tested fabrics are presented in Table 1.

Mono AR glass fabric observes high strength of 627 MPa, and brittle behavior with strain to failure of 5%, whereas the mono PP fabric exhibits lower strength, 397 MPa, with much more ductile behavior, of 58% strain to failure (Table 1). The toughness values up to failure are also very different when comparing the glass and the PP fabrics, with values of 9 J/cc and 127 J/cc, respectively. These results are expected. All hybrid fabrics exhibit strain at failure similar to the mono PP fabric of ~ 60%. Indicating that hybrid fabric even with high content of glass yarns of 75% can sustain high strain level. The toughness values at failure are rather different when comparing the different fabrics, depending on PP yarns content, greater PP content results in higher toughness values.

Looking at the overall behavior of the hybrid fabrics under tensile loading (Figure 1), two peaks are observed, the first is at low strain, ~ 2%, similar to that of the mono (100%) AR glass fabric and the second is at much larger stain, 25%-30%, similar to that of the mono PP fabric. It is appeared that the first peak increases with higher content of the glass yarns, while the second peak increases with greater content of the PP yarns. Figure 2 presents the stress values at each peak versus the PP yarn content. This figure clearly shows that AR glass yarns govern the first peak of the hybrid fabric, whereas the second peak is governed by the PP yarns. The ratio between these two peaks. i.e., which peak is higher, depends on the content of each yarn type within the hybrid fabric, whether more yarns are glass or PP. By fabric of 50P50G, the stress at the first peak (AR glass yarns contribution) is close to the stress at the second peak (PP yarns contribution). When considering the 75P25G, the second peak is greater than the first peak, which means that the maximum stress of the hybrid fabric is due to the PP yarns contribution. Note that based on the results presented in Figure 2, for content of ~64% PP and 36% glass, glass and PP yarns are expected to carry equal stress value of ~285 MPa. These specific contents provide critical point of yarn type contribution to fabric properties. Such values can be useful for design purposes of hybrid fabrics for a desired application.

Figure 2 shows the change in the average maximum stress (either first or second peak is greater, depending on glass or PP yarns content) and toughness at this stress versus PP content of the different hybrid fabrics. Reduction in fabric strength is seen when the PP yarns content is increased up to a point of 75%. Hardly any change is observed in strength between

75% and 100% PP, as the strength of 100% PP is even slight better than that of the 75% PP and similar to that of 50% PP system. This may suggest that fabric contains half amount of glass and half PP yarns develop almost similar strength than if only PP yarns are used for fabric production. When toughness (up to the maximum stress) is considered the situation is somewhat different; up to PP content of 50% hardly any change in toughness is observed, however when the PP content reaches 50% a significant increase in toughness is seen up to 75% PP with further improvement in toughness up to 100% PP. Note that the two curves, toughness and strength cutting each other at a content of ~ 64% (Figure 3) similar to that observed in Figure 2, suggesting again this content as a critical point.

These trends indicate that the glass yarns are controlling the fabric properties, strength and toughness up to a content of ~ 50%, whereas the PP contributes from this content and above. It is appeared that the main change in the hybrid fabric properties is in the range of 50% to 75% of PP yarns when considering strength and toughness at the maximum stress. Note that the strains at the maximum stress value might be very different whether the glass or the PP controlling this point. It can be concluded that a proper ratio between the glass and the PP yarns within the hybrid fabric will be in between 50 to 75% of PP yarns to allow similar contribution of glass and PP to the overall tensile behavior of the fabric. If considering Figure 2, such equal contribution to fabric properties can be at 64% of PP yarns.

Table 1: Tensile properties of the hybrid fabrics (without cement) are presented as function of the PP yarn content.

	property \ %PP	0	25	50	75	100
At failure	Toughness [J/cc]	9±2	63±8	86±9	109±3	127±14
	Strain [%]	5.2±2.3	64.1±9.9	64.4±6.8	62.1±4.5	57.6±5
At max stress	Strength [MPa]	627±46	579±49	389±77	322±11	397±5
	Toughness [J/cc]	6.2±1.0	7.3±1.7	5.4±1.8	66.2±3.7	77.7±9.0
	Strain [%]	1.9±0.3	2.3±0.5	2.3±0.5	30.7±1.6	30.1±3.0
At 0.25% strain	Stress [MPa]	76.1±23.5	75.6±14.3	59.3±15.0	39.2±7.7	8.4±2.2
	Toughness [J/cc]	0.10±0.03	0.11±0.01	0.09±0.03	0.06±0.01	0.01±0.01

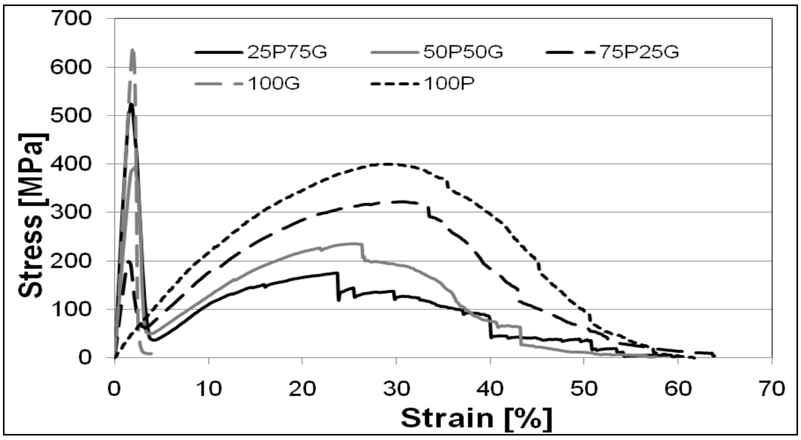


Fig. 1: Tensile behavior of the tested hybrid fabrics.

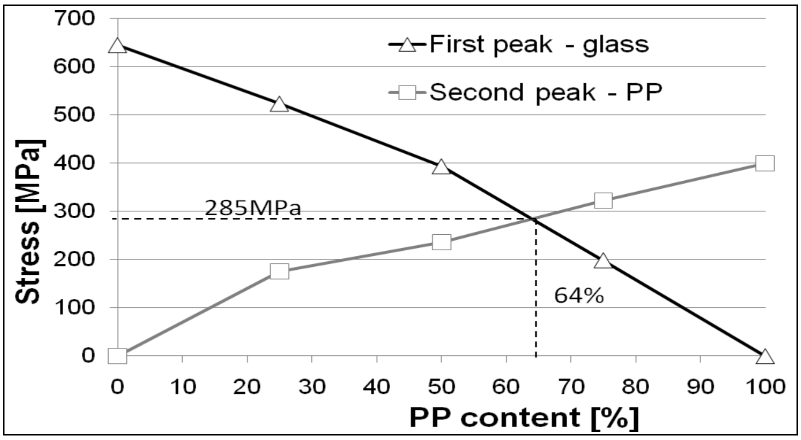


Fig. 2: Stress at first and second peaks of the different fabrics (see Fig. 1) vs. PP yarns content

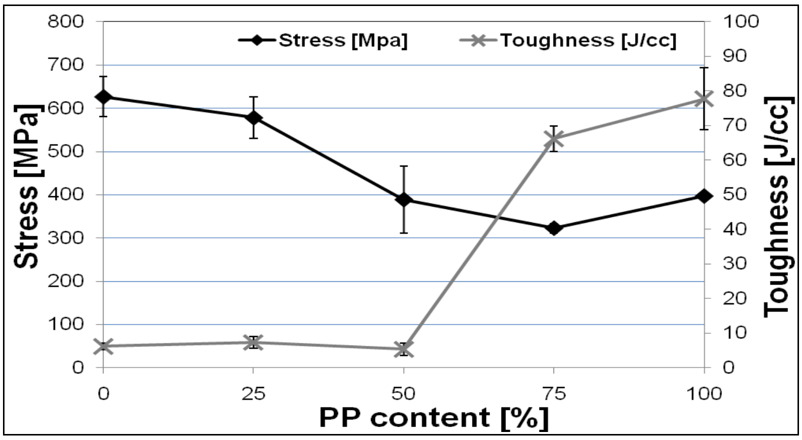
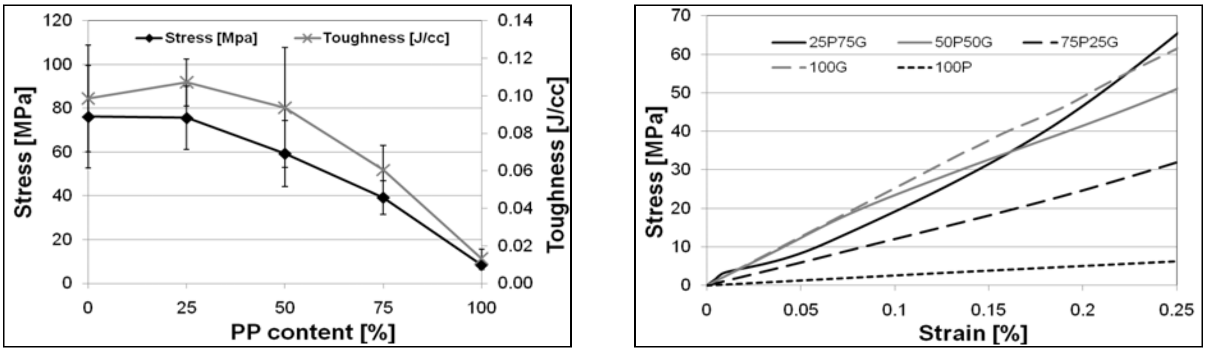


Fig. 3: The change in stress and toughness of the hybrid fabrics at maximum stress value, as a function of the PP yarns content.

3.1.2 Behavior at low strains (0.25%)

In order to better understand the influences of the glass yarns on hybrid fabric properties at low strain values the stresses and toughness at 0.25% strains are compared. This may provide better information on fabric stiffness. Figure 4b presents the stress-strain behavior of typical samples up to 0.25% strain. From Table 1 and Figure 4a it is possible to see that at low strains, AR glass yarns have the highest contribution on hybrid fabric properties, stress and toughness. i.e., controlled its stiffness in the hybrid fabric has the as discussed above. At this low strain level, for fabrics with 100% and 75% AR glass yarns the tensile stresses are quite the same, ~76 MPa. Once the content of AR glass yarns reduced to 50% and below, the tensile toughness and tensile stresses of the fabric are decreased in relatively linear behavior (Figure 4a). Significant reduction in fabric stiffness is observed when PP yarns content reaches 75% (Figure 4b). Hence, for low strain applications, fabrics with high content of AR glass are preferable where the 25P75G fabric provides the best performance.



(a) Stress and toughness behavior of the hybrid fabrics, as a function of the PP yarns content, at 0.25% strain.

(b) Stress-strain behavior of the different fabrics, at 0.25% strain.

Fig. 4: Mechanical properties of the hybrid fabrics, at determined strain of 0.25%.

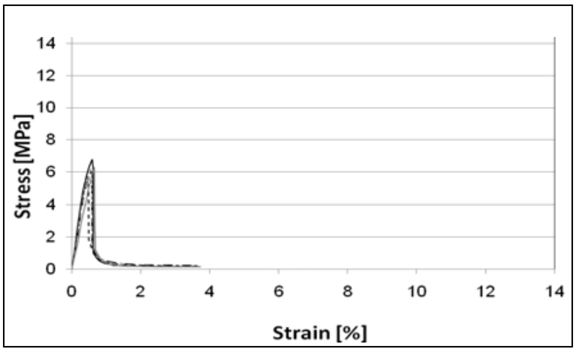
3.2 Composite

3.2.1 Overall behavior

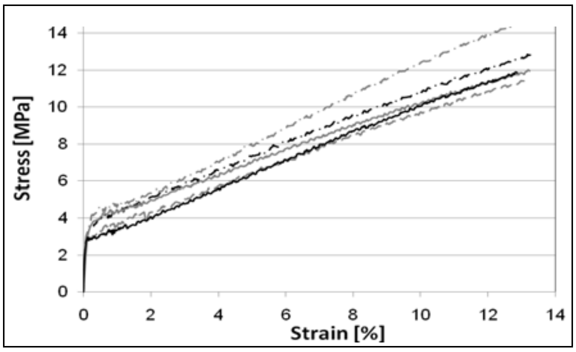
Table 2 presents the average stresses, toughness and strains of all tested composites at failure and at maximum stress.

Figure 5 shows the tensile behavior of all tested specimens for single glass composite (100G) (Figure 5a), single PP composite (100P) (Figure 5b) and 50:50 glass:PP hybrid composite (Figure 5c) systems. The mono composites, i.e. 100P and 100G, exhibit very good repeatability and low standard deviations of the overall tensile behavior. This means that the composite tensile behavior can be predicted with high precision. When looking at a hybrid composite behavior, the 50P50G for example, the inconsistent in composite tensile behavior of all tested specimens is clear, leading to less predictable composites. This knowledge is of importance in term of uniform production and use of the hybrid fabric-cement composites.

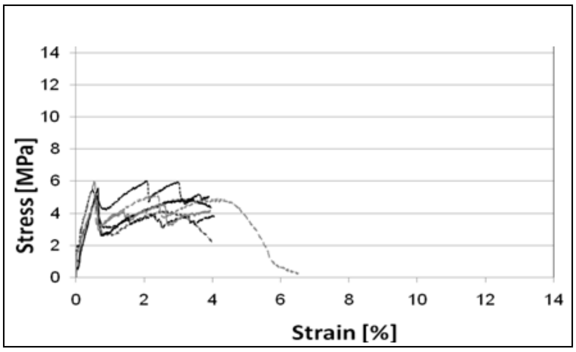
The brittle behavior of the mono AR glass composites compared to the significant ductile and tough behavior of the mono PP composites is clear, whereas the behavior of the hybrid composites is in between these two. This correlates well with the behavior of the fabrics discussed above, fabrics with greater toughness lead to composites with enhanced ductility, toughness and strain at failure (Table 2). Moreover, an overall improved tensile behavior of the mono PP composites as compared with the mono glass composite is obvious, as the PP composite exhibits strength of about 12 MPa and the glass of about 6 MPa. Note that the composites were subjected to 7 d accelerated curing which may cause low stress value of the glass system. It should be noted that the improved strength of the PP is at very high strains of about 12%, as from practical point of view such high strains are of less importance.



(a) 100G tensile samples.



(b) 100P tensile samples.



(c) 50P50G tensile samples.

Fig. 5: The tensile behavior of different systems: (a) 100P, (b) 100G, and (c) 50P50G, for all tested samples at each system.

Table 2: Tensile properties of the hybrid composites as function of yarn PP content

Strain point	%PP / property	0	25	50	75	100
At failure	Toughness [J/cc]	0.03±0.01	0.08±0.04	0.17±0.04	0.79±0.12	1.09±0.11
	Strain [%]	3.75±0.02	3.98±0.04	4.45±1.09	15.67±0.77	13.33±0.01
At max stress	Strength [MPa]	6.63±1.06	7.09±1.67	5.44±0.52	7.74±1.31	12.80±1.27
	Toughness [J/cc]	0.02±0.01	0.02±0.01	0.03±0.03	0.79±0.12	1.09±0.11
	Strain [%]	0.60±0.10	0.55±0.09	0.84±0.60	15.27±0.90	13.29±0.05

A comparison of the overall tensile behavior up to failure is presented in Figure 6 for all tested composite systems with the different hybrid contents.

When comparing the overall behavior of the composites up to failure it is observed that the maximum strain at composite failure varies significantly of the different tested systems. For 100% PP and 75% PP contents 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, less than 5%. The trend in toughness values is similar to that of the strains, significant increased in toughness of the composite is observed at PP yarn contents of 75% and 100% (Table 2). These trends correlate well with the fabric properties where the greatest stress values of 75% PP fabric are obtained at the second peak (Figure 1), i.e., the fabric strength controlled by the PP yarns. This suggests that at this PP content (75% and up) the PP yarns control also the composite behavior leading to high ductile composite. Below this content, 50% PP and less, i.e., above 50% glass yarns, fabric strength is mainly controlled by the glass yarns, leading to much more brittle behavior of the composite. Note that for 50G50P composite the strength is relatively high with strain to failure of about 5%, which can be beneficial from a practical point of view.

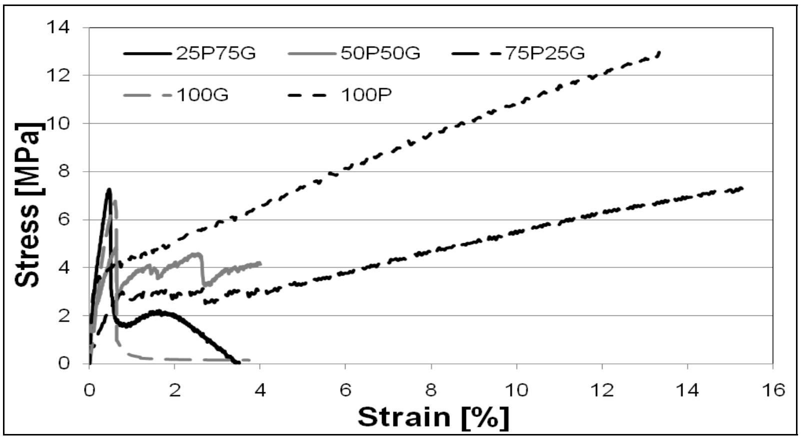


Fig. 6: The composites tensile stress-strain behavior.

3.2.2 Behavior at max stress

When comparing the tensile behavior of the different tested composite systems it is appeared that the maximum stresses developed at very different strain levels among the five tested systems. High content of PP systems (75% and 100%) showed strain of about 14% at max stress, whereas the other systems exhibited much lower strain values at around 0.7% when reaching the maximum stress (Table 2). These differences can be related to the properties of the controlling fabric, either PP or glass, on composite performance. Therefore, when comparing the results at the maximum composite stress value, such differences in strain values at this comparing point should kept in mind.

Figure 7 presents the maximum stress values and toughness up to this stress point of the different hybrid composite systems. Increase in composite toughness is observed when the PP content is reached 50% and up. Similar trend is observed for the strength values. The composite toughness behaves similar to the behavior of the fabrics (Figure 2), i.e., increased in toughness from 50% PP content and up. For lower PP contents (25% and 0%) no change is observed in toughness both for fabrics and composites. This suggests that the toughness of the composites controlled by 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 greater AR glass yarns content, the composites tend to have lower strength with higher AR glass yarns content. Note that the composites were cured under hot bath conditions which may cause chemical attack of the glass yarns surrounded by cement hydrates, leading to reduction in tensile behavior of the composites when high content of glass was used [11]. Other reasons for that behavior can be geometrical considerations of the reinforcing fabric, such as yarn tex, loop size, etc, which can affect the bond and the overall behavior of the composite, regardless the fabric properties [12]. It seems that between contents of 50% and 75% PP yarns there is a critical point, as the

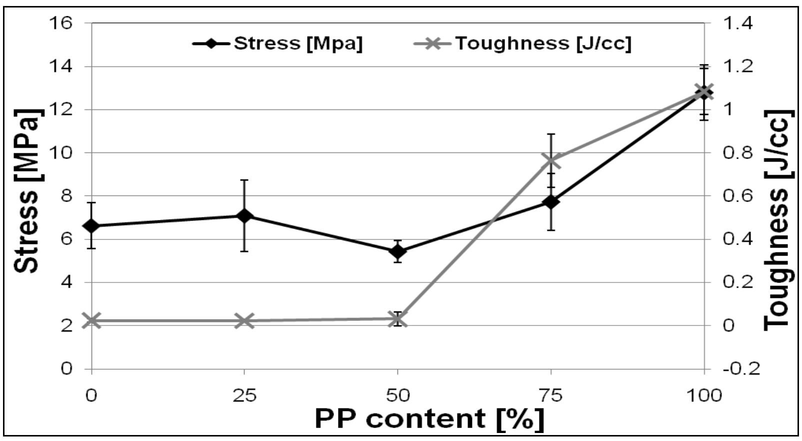


Fig. 7: The change in strength and toughness of the hybrid composites at the maximum stress value, as a function of PP yarns content.

composites and fabrics properties are dramatically changed (Figures 2, 5c and 7). This might be at least partly due to fabric properties, showed that at this content level the first peak which is related to the glass and the second peak which is related to the PP are relatively close (Figure 1).

The volume fraction (V_f) of each yarn type, either PP or glass, within the composite is presented in Figure 8 versus PP yarn content in the fabric. 2.3% V_f is observed for the mono glass composite and 3% V_f is seen for the mono PP composite. Equal volume fraction of glass and PP yarns within the hybrid composite is observed at 48% content of PP yarns. As mentioned earlier the glass and PP yarns within the hybrid fabric are expected to carry equal value of stresses at content of 64% PP yarns (Figure. 2). The change in maximum stress and toughness (at maximum stress) of the hybrid composites is in between 50% to 75% PP yarns content (Figure 7), i.e., the content of 64% PP is within this range. This may suggest that also for the composites the yarns are carried equal stress values at content of ~64% PP yarns. Above this content the PP yarns are carried most of loads and below this content the glass yarns are carried most of the loads, leading to significant change in toughness (at maximum stress) and strength of the composite at ~64% PP yarns content. Note that at this level of PP content the V_f of the glass (within the composite) is 1.85% and the V_f of the PP is ~1% (Figure 8).

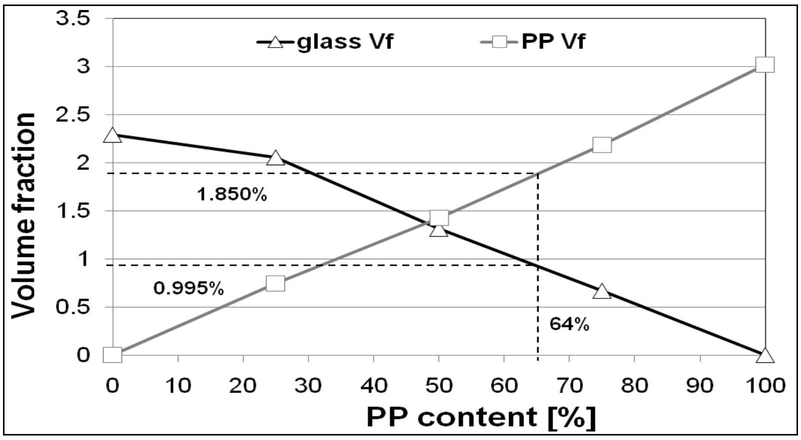
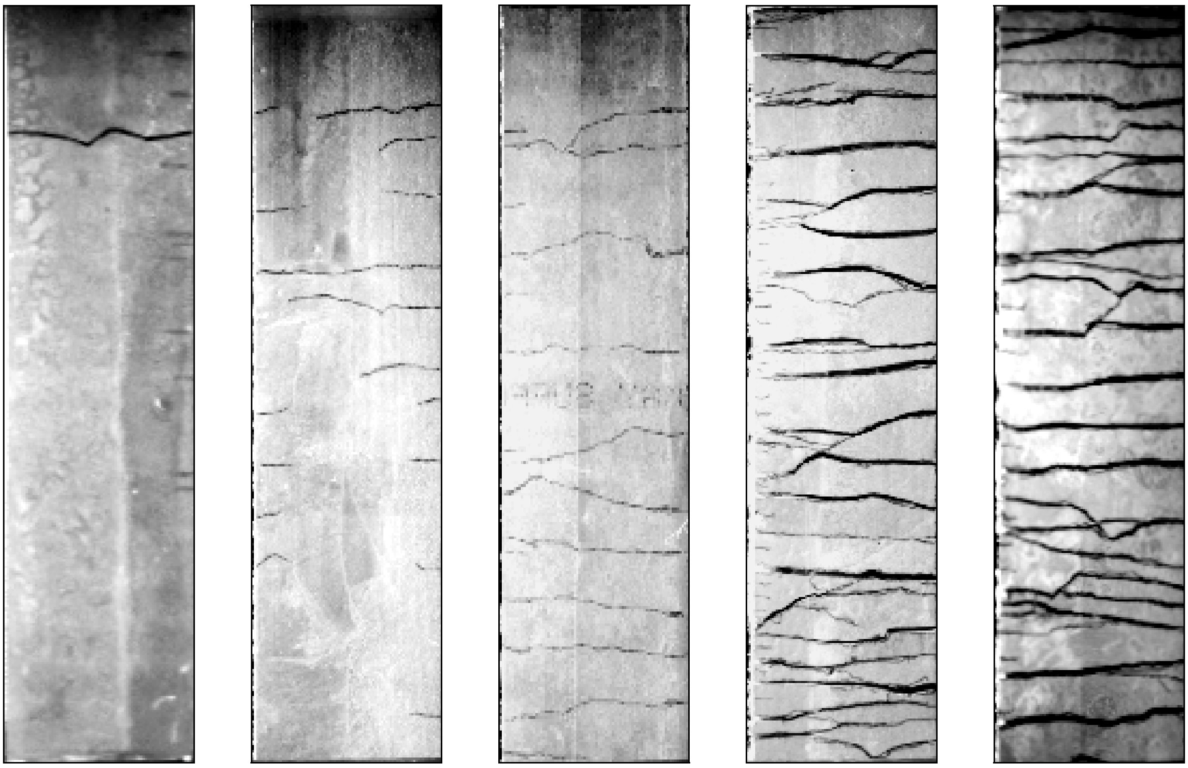


Fig. 8: Volume fractions of the glass and PP yarns within the composite.

3.2.3 Crack Pattern

The crack patterns of the different composites are observed in Figure 9. The presented images were taken when the composite reached its maximum tensile stress (out of a series of images taken at every 10 s during loading). In all samples, multiple cracking is observed. However, the crack width is quite different depending on the hybrid content. For 100G composites, the cracks are extremely small and can hardly see by naked eyes, this until one crack becomes the major crack and widen up to failure (Figure 9a). When increasing the amount of PP yarns in the hybrid composites the cracks become more visible (Figures 9b-d), while for 100P composites, the cracks can easily be recognized (Figure 9e). 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 presence within the composites, cracks widening becomes the dominant mechanism, leading to larger strains.



(a) 100G (b) 25P75G (c) 50P50G (d) 75P25G (e) 100P

Fig. 9: Cracking pattern of the different composite systems at maximum stress.

The cracks pattern may help to understand the behavior of the hybrid composites. The main influence on hybrid composites behavior is the ratio between the properties of the yarns within the hybrid fabric. As can be seen in Figure 1 for the fabric properties, the AR glass yarns tend to break first at a certain stress and strain values (first peak) depending on their content, then the PP yarns carry the loads up to a certain stress and strain values (second peak) depending on their content. Such relation between the two hybrid yarns may take place also when these fabrics are part of the composite, and affect the development of cracks within the composite. As first, the AR glass yarns are carried the loads and when those yarns are failed, the PP yarns carried the loads up to a complete failure of the composite. The PP yarns tend to pull out and tensioning during loading, due to their low modulus and low bonding with the cement matrix. Such sliding and tensioning of the PP yarns lead to relatively wide cracks. Therefore, when the PP content becomes high enough so the loads are mainly carried by the PP yarns, the cracks are wide and clearly observed, as seen in Figures 9d-e. This crack widening mechanism can lead to the extreme high strains of the cement composites with high content of PP yarns. However, when the AR glass are the dominant yarns, due to their relatively high modulus and their good bonding with the cement matrix, they tend to brake rather than pull out, leading to very fine cracks and low strains.

4 Conclusions

1. Combination of different yarn types in a hybrid fabric found to highly influence the tensile behavior of cement-based composites. Different hybrid ratios can lead to a range of properties from brittle composite to ductile composite with very high strains.
2. The fabric properties found to be highly depended by 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 govern by the PP yarns. Above 50% content of PP yarns the second peak was the greatest and below 50% content of PP yarns the first peak was the greatest.
3. A good correlation was found between fabric properties and composite behavior. It was shown that 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 and toughness. Therefore, high content of PP yarns leads to ductile composites whereas composites with high glass content are brittle. Optimum performances are suggested between 50% to75% content of PP yarns, i.e., providing ductile composite with relatively high strength. It was suggested that at hybrid system with 64% PP yarns content equal stresses will be carried by the glass and the PP yarns.
4. Hybrid composites are less predictable than non-hybrid (mono yarn) composites as the hybrid composites found to have inconsistent in their tensile behavior. Thus, when designing hybrid composites, safety errors should be considered much more carefully.

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