DEVELOPMENT OF HIGH TENACITY POLYPROPYLENE FIBRES FOR CEMENTITIOUS COMPOSITES.

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ABSTRACT: This study outlines the major findings of a research program aimed at developing high tenacity polypropylene fibres for cementitious composites. In the first part, it is shown by micromechanical modelling that the use of ordinary high tenacity PP fibres leads to unstable crack propagation and large crack opening at MOR of the composites. The same model indicates that by increasing the level of interfacial frictional and chemical bonding, large improvements of the fibre-cement properties (strength, cracking behavior) are to be expected. In a second part, we explain how we developed such fibres having improved bonding to cement by optimizing the composition of the sheath of high tenacity bicomponent core/sheath fibres as well as by applying surface coatings. The obtained improvements in the properties of fibre-cement and fibre-concrete composites in comparison with ordinary high tenacity PP fibres are described.

KEYWORDS: Polypropylene fibres, bicomponent fibres, fibre-cement, fibre-concrete

1 INTRODUCTION

The progressive substitution of asbestos in the European fibre-cement industry was initiated in the early 1980's. Two main fibre types were successfully used for this application, i.e., wood pulp fibres and polyvinylalcohol fibres. While the first ones were used as reinforcement of steamcured products destined to both external (cladding) and internal (partitioning, ceiling, etc...) applications, a combination of both fibre types was used in air cured products mainly destined to roofing applications (slates and corrugated sheets).

Although many other fibre types such as polycrylonitrile fibres (PAN), polyethylene fibres (PE), alkali resistant glass fibres (ARG), polypropylene (PP) nets and fibres, carbon fibres, (aromatic) polyamide fibres etc... are or were also used to some extent in this industry, none of them were used to the same extent as the above-mentioned fibres.

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2. Composite Modelling

With the ongoing changes in geometric representation, a composite model of the structure is presented. This model is derived from the geometric data obtained from various sources, including optical and electromagnetic imaging techniques. The model is further refined to incorporate the effects of environmental conditions and their influence on the structure.

The primary focus is on understanding the complex interactions between the various components of the structure. This includes the study of the stress distribution, material properties, and the overall behavior under different loading conditions. The model is designed to predict the structural integrity and to identify potential areas of concern.

Computer simulations are used to test different scenarios and to validate the model predictions. This approach allows for an iterative refinement process, where feedback from simulations is used to improve the model's accuracy.

The ultimate goal is to develop a comprehensive understanding of the structure's behavior, enabling effective design and implementation strategies. This work is crucial for ensuring the safety and longevity of the structure, as well as for optimizing its performance under various operational conditions.
The crack bridging law (crack bridging stress vs. crack opening) is obtained by averaging the contributions of those fibers that cross the matrix crack plane at the crack opens (1) or

The modeling of the fractured properties (LPR, MOR, work of fracture at MOR and crack width) uses the crack bridging law as the specimen geometry, material properties, load, crack length and a bridging stress distribution at crack equilibrium step (Kim et al. [4]).

2.1 FIBRE-CEMENT MODELLED USING A REFERENCE ORDINARY HIGH TENACITY PP FIBRE

Based on the pull-out test results obtained with an ordinary, high tenacity PP fiber, the following fiber and (fiber/matrix) parameters were chosen for the modelings:

The computed flexural stress vs. crack length using these data is shown in Fig. 1. When no fiber reinforced, the fracture mode is Mode I, with the inclusion of a fiber-reinforced case, Mode II is also possible. The flexural stress of the fiber-reinforced case is significantly higher than that of the unreinforced case (Fig. 1A). In other words, it is observed that the fibers show a crack propagation resistance, and the stress is significantly lower. The fractured level of 1 MPa, crack length of 0.5 mm, and the fiber length of 6.0 mm can be taken as an approximation.
When wood pulp is present, such “well” is no longer present, but a phase of unstable crack propagation can still be seen (Fig. 1B).

Figure 1B. Computed flexural stress vs. crack length of fibre-cement (PP + wood pulp fibres). “Strong” = machine direction; “weak” = cross direction.

Fig. 2 further shows the computed crack opening profile at MOR based on the same fibre and matrix parameters. The predicted maximum crack width (crack mouth opening) is quite significant at 158 μm. Calculated crack widths in the case of PVA fibres using the same model were only in the range of 20 μm.

Figure 2. Computed crack opening profile at MOR (ordinary high tenacity PP fibre).

From these results, it appears that using such PP fibres for this application leads to unstable cracking of the products and large crack opening.

2.2. COMPOSITE MODELLING USING HIGHER BOND STRENGTH VALUES

In a second step, the model was run using higher values of frictional and/or chemical bonding, while keeping other parameters constant.
As can be seen Fig. 3A, as \( t_b \) increases from the control value of 0.34 MPa, the area of unstable cracking gradually disappears. The MOR also increases from the control 35.7 MPa to 45 MPa at \( t_b = 0.7 \) MPa, to 47 MPa at \( t_b = 1.0 \) MPa. The size of the crack opening decreases by 50% when \( t_b \) increases to 1.6 MPa. Increasing the frictional bond means that it is harder for the fibres to pull-out so the springs are stiffer causing the MOR to increase and the crack opening to decrease. As crack length and corresponding crack opening increase, the fibre strength will be exceeded and the fibres will start to break which is the reason for the down turn in the top two curves. The higher frictional bond leads to a higher MOR, but also increases fibre rupture as a crack length that gradually decreases from the control of 3.7 mm.

![Graph A](image)

**Figure 3A.** Influence of the frictional bond \((\lambda)\) and of the interface fracture energy \((G_0)\) on the computed Mean Stress vs Crack Length curves.

As shown in Fig. 3B, increasing the chemical bond causes the region of unstable cracking to disappear and the MOR to increase from 35.7 MPa to maximum 52 MPa at 20 J/m². The LOP similarity increases from the control 16 MPa to 29 MPa. Increasing \( G_0 \) means increasing the flexural stress that must be applied to the fibres to make them debond from the matrix. This is before the fibres start to pull-out. The flexural stress required to break the chemical bond is higher than without such bonds, and the peak load will occur at a more shallow crack length.
which also means a smaller crack opening. An 80% reduction in crack opening is obtained for the highest interfacial chemical bond.

3 FIBRE DEVELOPMENT PROGRAM

As the preceding modeling work shows, for PP fibers, increasing the frictional and/or the chemical interfacial bond quite effectively improves the performances of fibre-cement.

The poor bondage of ordinary high tenacity PP fibres can be easily explained based on their low surface energy (hydrophobic character) and their low roughness.

The objective of the present experimental fibre development program was thus to produce fibres having on the one hand a high tensile strength and the other hand improved surface properties leading to higher fibre-cement bonds.

In order to produce such fibres, it was decided to build a pilot bicomponent fibre spinning plant, able to produce sheet/core types fibres. A view of this pilot line comprising a spinning stage, a drawing stage, a surface treatment and coating unit, a cutter and a bagging unit is shown in Fig. 4.

Figure 4. View of the pilot fibre line at Redco NV, Belgium

The structure of the fibres produced by this line is described in Fig. 5.

This technique allows to produce fibres whose shear layer composition, and thus surface properties, differs from their core. By using this technique, one can on the one hand optimize the shear layer for interfacial bond strength to cement, while minimizing the loss of strength and the cos increase usually associated with the presence of additives, on the other hand.
Figure 5. Structure of a sheath/core bicomponent fibre (E12C is a code name of one experimental fibres)

The first company to use this technology for the production fibres for cementitious composites was, to our knowledge, the company Daiwafo of Japan (e.g. Mino et al. [5]) which used fine fillers in the sheath.

In this line, we also included a surface treatment unit, as preliminary research had indicated that a coating treatment was already effective for improving fibre-cement properties and easy to implement (Vidts & de Lhoneux [6], Vidts & de Lhoneux [7]).

In the course of this program we investigated the use of a broad range of additives in view of their contribution to increasing the interfacial bond strength and improving the fibre-cement properties, with or without additional surface treatment. This was based on a careful analysis of the raw materials properties and processing conditions. Patents were filed about several aspects of this development.

Although fibre properties depended on many parameters, the strength of the bicomponent fibres reached a rather high level, at around 800 to 850 MPa. Table 1 shows the range of interfacial bond strength values, as measured by the pull-out tests, reached with different fibres from this production line.

Table 1. Influence of the sheath composition and surface coating on the interfacial frictional and chemical bonds.

<table>
<thead>
<tr>
<th>Additive in the sheath</th>
<th>Surface coating</th>
<th>(\tau_s) (MPa)</th>
<th>(G_s) (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>No</td>
<td>0.22</td>
<td>-</td>
</tr>
<tr>
<td>None</td>
<td>Yes</td>
<td>0.4 to 0.72</td>
<td>-</td>
</tr>
<tr>
<td>Mineral filler</td>
<td>No</td>
<td>0.64</td>
<td>-</td>
</tr>
<tr>
<td>Copolymer A</td>
<td>No</td>
<td>0.82</td>
<td>-</td>
</tr>
<tr>
<td>Copolymer B</td>
<td>No</td>
<td>1.51</td>
<td>1.4</td>
</tr>
<tr>
<td>Copolymer C</td>
<td>Yes</td>
<td>1.02</td>
<td>-</td>
</tr>
<tr>
<td>Copolymer D</td>
<td>Yes</td>
<td>0.76 to 1.1</td>
<td>0.07 to 0.10</td>
</tr>
</tbody>
</table>
Different mechanisms can explain the observed improvements of interfacial bonding, such as the presence of functional groups able to chemically bind with cement (coating and copolymers), an increased roughness of the surface (fillers, coating), a reduced surface stiffness, etc.

4 PROPERTIES OF FIBRE-CEMENT PRODUCTS

Mechanical properties of laboratory composites manufactured using 1.7 wt% of different PP fibres are shown in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOR (MPa)</td>
<td>10.1</td>
<td>13.1</td>
<td>14.0</td>
<td>16.1</td>
</tr>
<tr>
<td>Work of fracture at MOR (J/m²)</td>
<td>317</td>
<td>3228</td>
<td>3471</td>
<td>4193</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.47</td>
<td>1.48</td>
<td>1.46</td>
<td>1.49</td>
</tr>
</tbody>
</table>

These results indicate a large influence of the surface treatment as well as of the sheath composition on the strength and toughness of the fibre-cement composites, as was expected based on the increase of the interfacial bonds observed in the pull-out tests.

In addition, as Figure 6 shows, the stress-strain curves of the composites made with the bicomponent fibres containing the copolymer D do no longer show typical load drops of ordinary PP fibres which can be attributed to crack extensions during the loading.
Figure 6. Stress-strain curves in three points bending test of laboratory composites in air-dry conditions containing 1.5 wt % fibre. 
A = ordinary high tenacity PP fibre; 
B = Coated fibre with polyolefinic copolymer D in the sheath.

In view of the achieved fibre-cement properties improvements, industrial production of fibre-cement roofing was initiated using some of these new fibres in different countries. The most important productions were made in Latin America (Peru, Colombia, Argentina, Chile) where about 300,000 M2 roofing products (corrugated sheets) were sold on the market (Fig. 7).

Figure 7. Fibre-cement roof made in Peru using biocomposites PP fibres from Redco pilot line.

5 FIBRE-CONCRETE

Properties of concrete containing 0.9 kg/m³ of (A) an (low tenacity) PP fibre for concrete and (B) a coated fibre (without additive in the sheath) from the pilot line are shown in Table 3.
Table 3. Properties of fibre-concrete at 0.9 kg of fibres per m³ tested according to NBN B15-238 & B15-239 (Belgian Standards) (tensile strength) and according to ACI commission 544 (J. Amer. concr. Inst. 85, 589-93).

<table>
<thead>
<tr>
<th></th>
<th>Bending strength (max. value) N/mm²</th>
<th>Impact Number of impacts before failure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary PP fibre for concrete</td>
<td>1.6</td>
<td>11</td>
</tr>
<tr>
<td>Coated PP fibre from pilot line</td>
<td>1.8</td>
<td>75</td>
</tr>
</tbody>
</table>

Although no significant difference between both fibres can be seen as far as the bending strength is concerned, the improved PP fibres provide higher impact strength.

More experimentation is nevertheless needed, as significant scatter in the individual impact test results were observed.

6 CONCLUSIONS

This study has shown that the interfacial bond strength is a key factor in the development of PP fibres for fibre-cement and fibre-concrete.

By optimizing the surface properties of high tenacity fibres, it is possible to reach satisfactory fibre-cement properties.

The commercial availability of such fibres in the future will encourage the production of asbestos-free products, particularly in low income countries.

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REFERENCES


