OVERVIEW OF FACTORS CONTROLLINGSHRINKAGE OF FIBRE CEMENT REINFORCED BY ORGANIC FIBRES

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ABSTRACT

Fibre cement drying shrinkage can lead to edge cracking during storage. Carbonation shrinkage is also associated withcracks in fibre cement. This paper provides a systematic investigation on the factors that influence shrinkage of fibre cement reinforced with organic fibres.The effects of porosity and pore size distribution, cement type, composite formulation and use of admixtures wereinvestigated using laboratory and industrial samples. An overview of the experimental results is given. We also present various industrial strategies that canbe used to reducetheshrinkage of organic fibre-reinforced cement.

KEYWORDS

Drying shrinkage; Carbonation shrinkage; Fibre cement; Edge cracking prevention.

INTRODUCTION

Fibre cement shrinkage can result in edge cracking during storage.The shrinkage occurs because thepore size distribution of the fibre cement favoursthe action of capillary pressure.This pressure affectsthe inner walls of the pores causing shrinkage at themacroscopic scale.The shrinkage rate is high forfibre cement, whichcan cause cracking.The causes that contribute to shrinkage are a large drying area and a large pore volume coupled with appropriate porosity.The large consumption of cement and fillers induces porosity,favouringan increase in capillary pressure and subsequent shrinkage. Our 10 year-long studyshows that in practice, fibre cement drying shrinkage inindustrial products varies from 1.5 to 3.5 mm/m.

The way that the corrugated sheets and cementitious boards are stored in the plants also creates favourable conditions for cracking. The upper sheets tend to bend due to upper face drying shrinkage when exposed to an unsaturated environment. Cracks usually appear on the longitudinal edge transverse to the corrugated sheet waves, possibly due to differential drying and shrinkingbetween the dry exposed edges and the wet core of the pileof tiles (Figure).

Edge cracking is an important industrial problem thatoccurs frequently in air-cured fibre cement reinforced with organic fibres and in asbestos-free technologies (de Souza and John, 2010).Figure shows a pile of fibre cement tiles. The differential drying, which is the major cause of shrinkage, can give riseto substantial tensile stress that can cause cracking (Akers and Garrett, 1983).
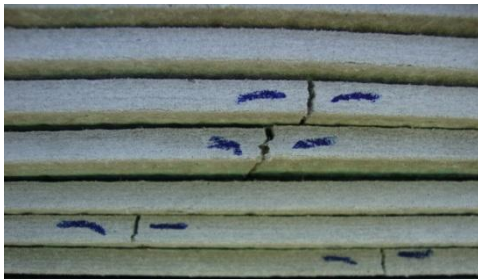
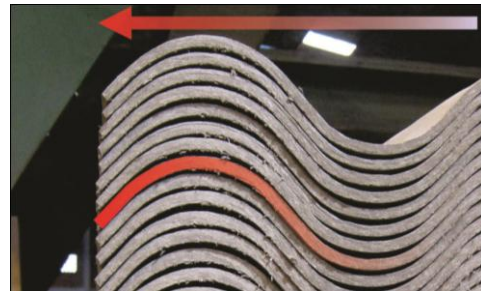**Figure 1 – Edge cracking during storage of the fibre cement tiles.**

Figure 2 – Fibre cement tiles in storage.The red colour indicates that moisture is lower near the edge.

The way that the cement is stored also favours differential carbonation shrinkage. Carbonation is higher at the edge because the diffusion of air containing CO_2 is more limited in the poorly-ventilated high-humidity pile core than at thetile edge.

This paper systematically analyses how different factors influence drying shrinkage of fibre cement reinforced with organic fibres.

METHODOLOGY

This work presents an overview of the main results of a long-term research study on possible strategies to control drying shrinkage forasbestos-free fibre cement.

The majority of the results presented are samples of fibre cement produced in the laboratory. The materials were originally obtainedfrom commercial sources. Moulding of the samples was performed according to the methodology described by Savastano et al.(2005), with some adaptations. This method uses the same principlesof filtration and compressionasHatscheck's process.Some of the sampleswerefrom a corrugated fibre cement factory. The samples were submitted to thermal curing for approximately18 h.The detailed experimental procedures for every test were described previously(de Souza, 2014).

THE EFFECT OF POROSITY AND PORE SIZE DISTRIBUTION ON SHRINKAGE

Hygroscopic movement, carbonation and chemical shrinkage occurred in the hydrated cement compounds. Theseare the three factors that can promote shrinkage in cementitious materials.The fibrecement favours these factors due to itshigh porosity (large hygroscopic movement and ease of diffusion of CO_2) and large cement content (favours carbonation and chemical shrinkage).

The total porosity of commercial air-cured fibre cement ranges between 30 and 45%, which is of the same magnitude asmortars (ranging from 30% to 50%, according to (Cardoso, 2009)), and significantly more than concrete, which isapproximately 15% (Sato; Agopyan, 1998). Furthermore, the pore size distribution favoursan increase in the capillary pressure and thus contributes to shrinkage.

Figure shows the pore size distribution of a typical NT fibre cement sample.Clearly, the profile can vary due to several factors such as formulation, raw materials andcuring.According to Mindess(1981), capillary pressure onlyoccurs in the capillary pores (diameter between 0.01 and 10 micrometres), where it ishigher in mesopores (Figure -II) and lowerin macropores (Figure -III).Of the total porosity

of 35%, approximately 30% of the porosity is frommesopores and macropores.Thus, we can estimate that macropores causeapproximately 50% of the total drying shrinkage of the cement.
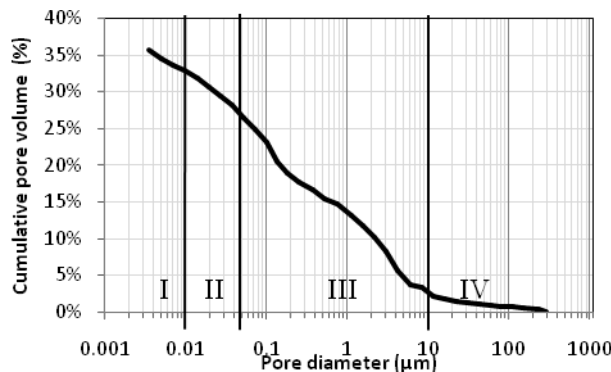

Figure 3 – Pore size distribution of typical NT fibre cement reinforced with polymeric fibre(de Souza, 2014). I-gel pore; II-mesopores; III-macropores; IV-defects (Mindess, 1981).

In general, increasing theporosity increases the drying shrinkage. However, the pore size distribution influences the shrinkage once the capillary pressure occurs in the mesopores and macropores. The porosity can be controlled by changing the packing, e.g., by varying the average diameter of thefiller particlesor bychanging bothrole andstack pressing pressure of the fresh fibre cement. Figure .a shows that theporosity decreases linearly from 52.5% to 38.0% whenapplying increasing compression stress from 0.125 MPa to 1.0 MPa. The porosity remainsalmost constant for higher-pressure, perhaps becausea small porosity volume increase for too high of a pressures has too much elastic energy.In the second situation, the porosity of the fibre cement is reduced by increasing the packing degree by varying the average filler (limestone) size. Smallerparticle sizesproduce lowerporosity values forthe samples(Figure .a).
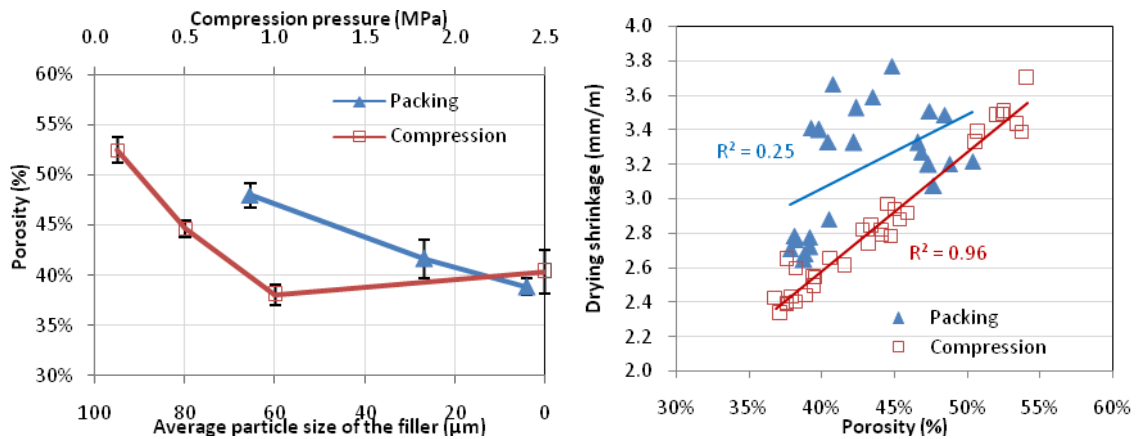

(a)(b)

Figure 4 – (a) Porosity as a function of compression pressure and according to the filler particle size. (b) Correlation between porosity and drying shrinkage at 14 days.

The compaction of fibre cement reduces the volume of the defects (Figure .a), which does not cause shrinkage.It also proportionally reduces the quantities of macropores, mesopores and gel pores.For this reason, the correlation between porosity and shrinkage is high ($R^2 = 0.96$) (Figure .b).The increase in packing degree reduces the porosity of fibre cement (Figure .a), but the pore size distribution is different for each filler used, creating a favourable condition for shrinkage when the

filler has amean diameter of 26.8 μm.The macropore volume was higher for this sample than forthe others samples (Figure .b), which explains the higher shrinkage (3.50 mm/m).The other samples had an average drying shrinkage of 2.75 mm/m (filler 4.0 μm) and 3.29 mm/m (filler 65.5 μm).
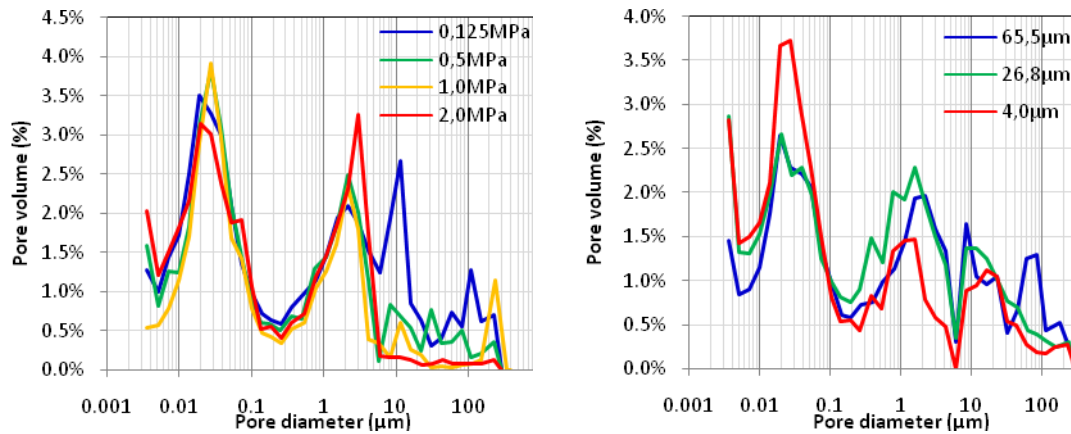
(a)(b)

Figure 5 – Pore size distribution of the samples (a) subjected to different compression pressures and (b) subjected to different degrees of packing.

THE EFFECT OF THE RAW MATERIALS AND FORMULATION ON SHRINKAGE

Changing the product composition is also a possibility. A well-known example is the effect of mineral admixtures, such as blast furnace slag and fly ash,whichcause a refinement in theporosity. On one hand, they cause a reduction inthe pore volume in the range of2.33 to0.03 mm, which are quite large pores that can generate comparatively low capillary forces. Onthe other hand, they tend to increase the amount of mesopores, which generate comparatively larger capillary forces upondrying.For this reason, the overall shrinkage increases when limestone cement filler isreplaced by silica fume, pozzolan or slag (Giordano et al., 2009).Asimple change inthe cement type can lead to a 30% reduction indrying shrinkage.

Hydrated cement paste is a large fraction of the fibre cement volume. Therefore,it has a strong influence on shrinkage.In practical terms, it is possible to change cement composition, e.g., by varying the type of cement as well as, within limits, its volume fraction. These factors may cause changes inthe volumesofhydrates, especially C-S-H, as well inthe hydration kinetics due to differences in the rate of hydration of various cement compositions. All of these factors will affect the pore size distribution, Young's modulusand mechanical strength over time, which will therefore influence the shrinkage and cracking.

Figure shows results forsamples produced by varying cement content from 20% to 80% of the dry materials.The cement content was increased by replacing the filler. As a general tendency, the shrinkage increased asthe cement content decreased.The final value was influenced by the equilibrium moisture content (after 14 days of dryingat 50% RH and 23°C).Lower cement contents had lower equilibrium moisture levels due to their lower surface areasand greater volumes of water trapped in the C-S-H lamellae. C-S-H pores are approximately 1 nm (Mehta and Monteiro, 2008) and will only dry slowly when exposed to very low relative humidity levels between 15 and 35% (Sato, 1998).

Moreover, at such low levels of moisture, the micropores and gel pores no longer have a continuous moisture phase, which is required for the formation of menisci that cause shrinkage by capillary depression (Baroghel-Bouny, 2007; Taylor, 1997). Increasing the amount of cement also tends to reduce the presence of larger pores.
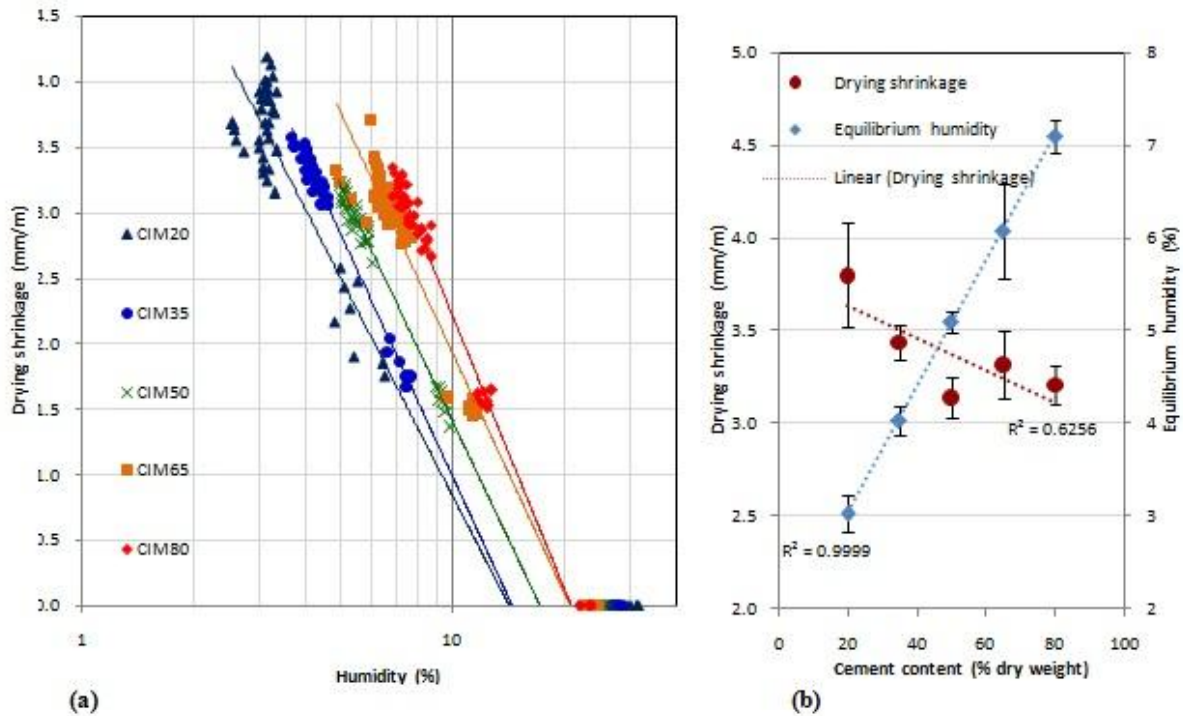

Figure 6–Influence of cement content on drying shrinkage of the fibre cement samples. The cement content in the samples was20% (CIM20), 35% (CIM35), 50% (CIM50), 65% (CIM65) and 80% (CIM80).(a) Humidity versus drying shrinkage. (b) Cement content versus equilibrium humidity and total drying shrinkage at 14 days.

The effect of fibre volume on shrinkage is also of interest. Cellulose fibres are highly hygroscopic, i.e., water can be absorbed in the bulk of thenon-crystalline fraction(Zografi et al., 1984)causing a large amount of shrinkage when drying. Therefore, cellulose fibres increase the retention of water, resulting in a higher porosity of the composite. Additionally, cellulose fibres have internal pores (lumens)(Tonoli et al., 2009)andinfluence global packing. Therefore, increasing the cellulose content will increase the amount of pores,mainly which are between 2.33 and 0.03 μm in diameter (macropores and part of mesopores). An increase incellulose from 1% to 5% will increase theporosity to approximately7.6%.The shrinkage was directly correlated with the porosity (Figure .a).
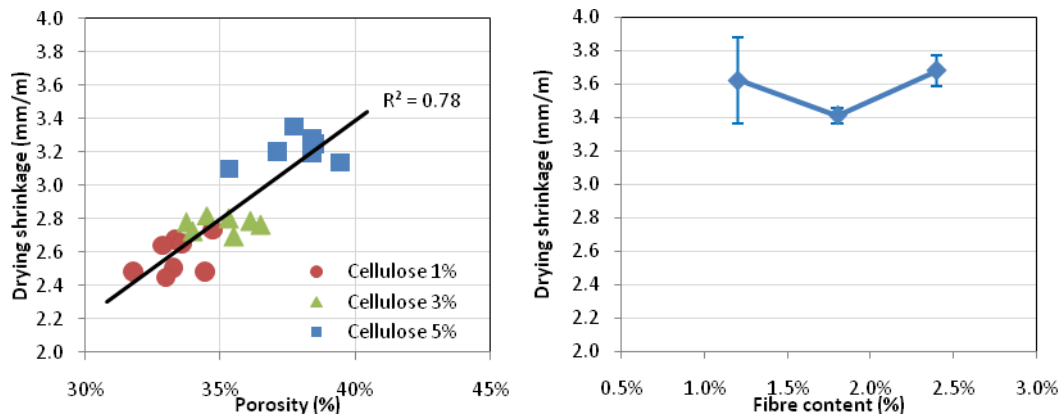
(a)(b)

Figure 7 – Drying shrinkage of fibre cement as a function of (a) cellulose fibrecontent varying from 1%, 3% and 5% and (b) PVAfibre content.

Polymeric fibres such as PVA have no porosity and do not absorb water. High contentsof PVA fibres slightly increase the total porosity, possiblybecause packing becomes increasingly difficult. The influence on shrinkage, however, is very small – close to 0.27 mm/m (Figure .b).Onthe other hand, the presence of higher amounts of this fibre will increase the number of cracks, reducing theirwidths and making them more difficult to spot.
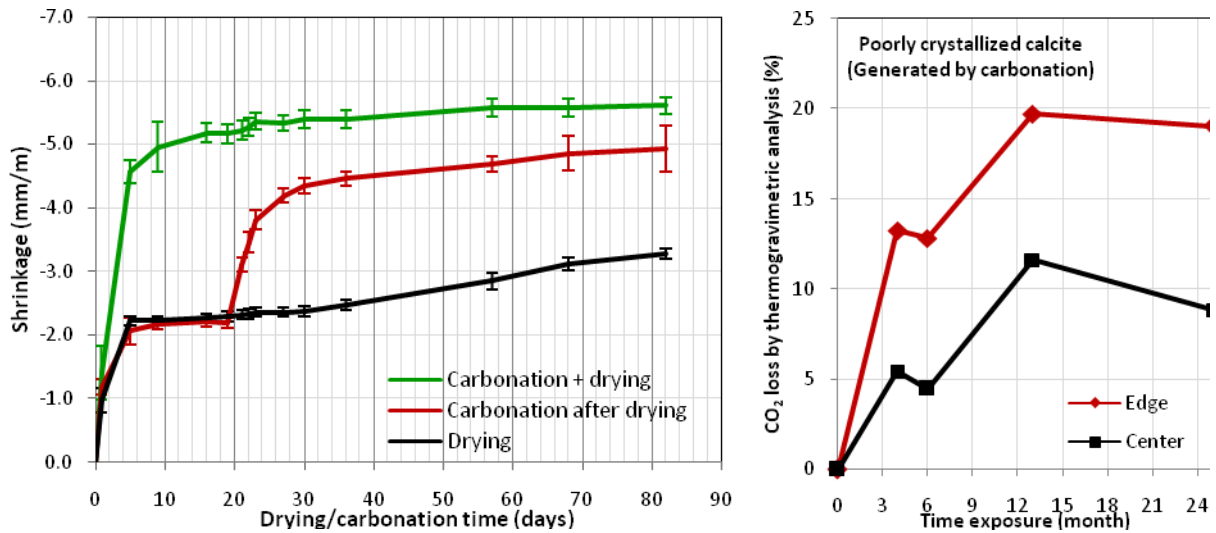

CARBONATION SHRINKAGE

Carbonation involves the diffusion of carbon dioxide into the material. Fibre cement sheets are thin and have large surface areas. They also arehigh porous. These two aspects combine to allow for fast drying and diffusionof CO_2. CO_2 will react with hydrated products, mainly calcium hydroxide, resulting in changes inporosity, water loss and shrinkage. Because the volume fraction of the cement paste in the fibre cement is much higher than in the concrete, shrinkage due to carbonation is higher too. In just 14 days of exposure to anenvironment of 5% carbon dioxide, dry fibre cement will shrink approximately 2.2 mm/m, with formation of 18.2 g $CaCO_3$ per 100 g of cement.

Figure .a shows the shrinkage results for thefibre cement samples submitted to different cycles. The reference sample was dried in a CO_2-free climatic chamber with 50% relative humidity. Thisexperiment used drying shrinkage and no carbonation. A second sample was dried in the same CO_2-free environmentuntil it reached a constant weight (19 days) and was subsequently submitted to accelerated carbonation in an atmosphere of5% CO_2 with50% RH.This sample was carbonatedafter hadbeen properly dried. The third sample was exposed to drying at 50% relative humidity in an environment of5% CO_2. This sample, which was subjected tosimultaneous accelerated carbonation and drying had a total carbonation and drying shrinkage almost twice of the samplesubmitted to drying only. The shrinkage of this sample was also approximately 10% higher than the samplesubmitted to drying followed by carbonation. This can be attributed to the effect of the porosity changes due to carbonation and drying.

Figure .b shows the amount of CO_2fixed by carbonation atthe edges and in the centre of a stockpile over 25months. The tile edges had higher shrinkage than the pile core,not only due to drying but also due to carbonation. Differential shrinkage occurredbecause it takes a long time for $CO_2$to diffuse to the core regions of stockpile, which also loses water at a much slower pace than the surface.

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Thediffusion of CO_2 in the wet fibre cement in the core of the stockpile wasalso much slower because diffusion of CO_2 is 10^4-10^6 times slower in water than it is in air (Neville, 1997). Therefore, carbonation can explain the fact that the cracks continued to occur in stockpiles of the fibre cement material exposed to the environment for a long time.

(a)(b)

Figure 8 – (a) Shrinkage as a function of drying time and accelerated carbonation (in an atmosphere with 5% CO_2). (b) Amount of CO_2 from $CaCO_3$ decomposed at 700°C by thermogravimetry (poorly crystallized calcite generated by carbonation).

INDUSTRIAL STRATEGIES ALLOWING THE REDUCTION OF DRYING SHRINKAGE

The diagram below (Figure) illustrates the extent to which eachvariable can influence the shrinkage of cement. The key to controlling the shrinkage is to control the porosity. The total porosity can be reduced by compression in the forming roller or by stack pressing and packaging. Reducing the cement content, without controlling packing can increase the drying shrinkage,but at the same time,the carbonation shrinkage will be reduced.
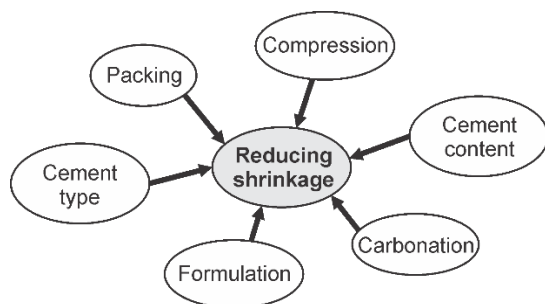

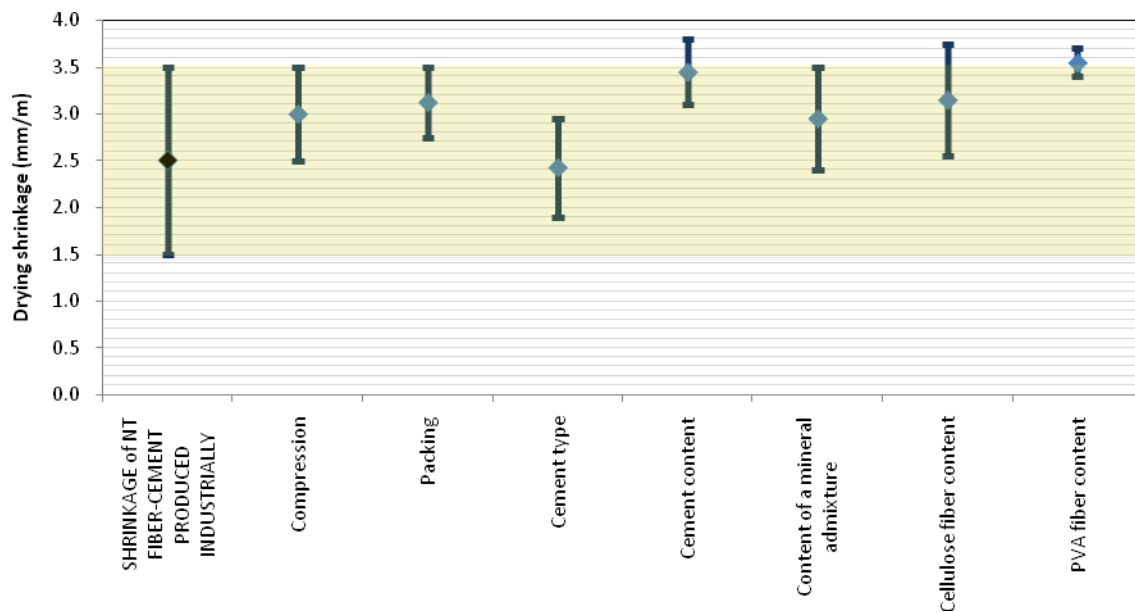**Figure 9 – Strategies for reducing shrinkage in NT fibre cement.**

Figure 10 –Range of variation for theexperimental results obtained forlaboratory samples compared with the range observed for the industrial Hatschek process(yellow stripe).

Figure shows the amplitude of shrinkage of NT fibre cement produced industrially over an almost 10 years-longexperiment as a result of ordinary variationsinthe industrial process, including changes in theformulation and process. The combined action of several factors results in a shrinkage range from 1.5 to 3.5 mm/m.In the lowest side of this 2 mm/m interval, the fibre cements performs well with very low risk of edge cracking. Onthe other side of this interval at the highest levels of shrinkage, the risk of edge cracking is very high.The potential foreach investigated variable to reducetheshrinkage can be easily compared with the range of shrinkage that occursin industry.

CONCLUSION

We demonstrate that there are many available strategies forcontrolling drying and carbonation shrinkage in industrial operations. A careful combination of these strategies will significantly reduce the riskof the edge-cracking of fibre-cement board piles.

When fibre-cement remains at stockpiles for short periods of time, it is important to controllingdrying shrinkage. This is achieved by reducing the porosity, especially the volume of the mesopores and macropores. Increasing pressure on the forming cylinder, reducing cellulose fibres and avoiding cements containing blast furnace slag and fly ash are effective options. Reducing the porosity by changing the packing does not always result in a reduction inshrinkage. A reduction of cement content can lead to an increase inshrinkage.

When fibre-cement sheets are stored for long periodsin piles, differential shrinkage due to carbonation isalso an important risk factor to consider.

ACKNOWLEDGEMENTS

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