The influence of processing parameters on the strength and toughness of asbestos cement composites

S. A. S. Akers* and G. G. Garrett†

Synopsis Some basic understanding of the influence of production processing parameters on the strength and toughness of asbestos cement composites should certainly facilitate investigations aimed at asbestos fibre replacement programmes. In this work it has been shown that no single processing variable can be isolated and studied independently using the industrial Hatschek process, and that changes in processing variables such as fibre content, pretreatment, pressing pressure, and cement specific surface area are directly associated with changes in porosity and water–cement ratio. By implication, useful directions emerge based on economic considerations of optimised processing-property combinations.

Keywords Fibre composites, asbestos, composite fabrication, asbestos cement products, production control, process variables, modulus of rupture, density, impact resistance, composite materials, optimisation, quality control, strength, toughness, porosity.

INTRODUCTION

It is not necessary to debate the purpose of fibres in a cement-based fibre composite material. It is important, however, especially in cement-based composites consisting of chopped or discontinuous fibre distribution, to optimise the full reinforcing potential of the fibres contained in the material. The first basic requirement, of course, is that the fibres are completely surrounded by hydrated cement particles in order to maximise bonding area. The achievement of such an objective is less easy in practice, however, as will become evident in this paper.

If, as an example, the processing parameter of 'fibre content' is considered first and it is assumed that all other variables remain unchanged, it is logical to suggest that if fibre content were progressively increased, it would be theoretically possible to achieve an optimum reinforcing capacity of the fibres at the point where the specific surface area of the fibres achieves that of the hydrated cement. This optimum value would thus represent the maximum available surface coverage of the cement in order to achieve the optimum mechanical strength of the composite material.

Several similar arguments may be proposed concerning parameters such as water–cement ratio, porosity, cement specific surface area and other relevant variables. It will be deomonstrated, however, that such theoretical objectives are exceedingly difficult to implement in practice due to the complex manner in which asbestos cement is commercially produced, typically using the so-called 'Hatschek Process'. This process is well established and well documented [1], and need not be described in any detail in this paper.

It is the purpose of this paper, then, to describe the influence of processing parameters such as fibre content, pre-treatment, pressing pressure and cement particle size on the mechanical properties (strength and toughness) of the asbestos cement composite through the effect such variables have on porosity, water–cement ratio, fibre and cement specific surface area. Certainly, this task is not straightforward since many of the above mentioned variables are interrelated and it is not possible to isolate one entity without influencing the others. The exercise is further complicated by the fact that it is possible to produce large variations in mechanical properties of a single composite mix by slight adjustment of the rate of production, for example, or filtration rate. In other words it is not possible to predict the quality of the product produced by merely prescribing mix proportions.

Using carefully designed experiments an attempt has been made to study the above-mentioned processing parameters on a scaled-down production process known as the 'Mini-Hatschek' process. As this process is industrially orientated, dependent on industrial processing techniques, the experimentation is automatically limited in certain aspects. Some investigations described in this paper have been conducted to the limit of the equipment and techniques available.

* Ametex AG, CH-8867 Niederunen, Switzerland.
† Department of Metallurgy, University of the Witwatersrand, Johannesburg, R.S.A.

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It should also be pointed out that the investigations have primarily been aimed at studying the potential mechanical properties of the asbestos cement composite and as such are not necessarily specifically oriented towards economic viability. However, the results contained in this paper certainly add to the understanding of the processing-property relationship in asbestos cement composites and trends demonstrated in these results could well supply useful information to the asbestos cement industry especially when considering asbestos fibre replacement programmes.

EXPERIMENTAL PROGRAMME

Processing parameters

Collering Crude chrysotile asbestos fibres received from the mine are 'collered' wet using a Kollergang. The process consists of a mechanical milling action where two large millstones rotate and tend to flatten and separate asbestos fibre bundles. This results in the opening and splitting up of relatively large fibre bundles into smaller dimensions. Results presented represent collering times of 20, 40 and 60 minutes.

Fiberisation The fiberisation process is carried out after collering and takes the form of mechanical spinning. Utilising a clover-leaf container, the collered fibres are spun in water suspension by means of a rotating propeller.

This process results in a 'fluffing' of the fibre bundles in the water suspension involving a fibre opening and an increase in specific surface area of the fibre mass in suspension. Two extreme fiberising times were chosen and the results presented represent 1 minute and 60 minutes spinning times.

Cement Particle Size A relatively coarse portland cement was ground using a ball mill in order to achieve varied degrees of cement fineness. The cement particle sizes presented represent Blaine values of 2500, 4100 and 5500 cm^2/g. These were sampled at the appropriate stages of ball-milling.

Water–Cement Ratio This parameter was varied by a simple adjustment of the suction below the belt on which the wet fibre cement mix is conveyed on the Hatschek machine.

The water–cement ratio was determined on a fully cured sheet using a method in accordance with the British Standards B.S.1881:Part 6:1971. A small correction factor was also necessary due to the water contained in the fibres themselves.

Pressing Pressure applied to the 'green' sheet immediately after production results in water being expelled from the 'wet' composite. In this way higher densities may be achieved in the fully cured product. Pressures applied using a standard press were 1221, 2443 and 6107 kPa.

Production and testing

The Mini-Hatschek process was used for all the experiments described in this paper, and unless otherwise mentioned, all sheets made on the Mini-Hatschek were first left between steel form plates for 24 hours. After this time specimens were cut from the central portion of each sheet and cured in a controlled environment (i.e. 99.5% humidity and 23 ± 1°C).

A standard, four-point bend test was used for the determination of modulus of rupture. Impact resistance was measured using a modified Zwick apparatus used for standard Charpy impact testing. Density measurements were made using a conventional water submersion technique used widely in the asbestos cement industry.

All data points on the curves described in the following sections represent the average and standard deviation of eight specimens (unless otherwise stipulated).

RESULTS AND DISCUSSION

Results in this section will be discussed in terms of variations in strength and toughness related to changes in the following processing-related parameters:

a. fibre mass fraction, density and water–cement ratio;
b. fibre specific surface area; and
c. cement specific surface area.

Fibre mass fraction, density and water–cement ratio

Figures 1a and 1b represent the change in modulus of rupture and density respectively with progressive increase in fibre content and applied pressure. The following trends are evident from these results.

a. Increasing the fibre content results in a progressive decrease in density (representing a progressive increase in porosity) (Figure 1b).
b. Despite this progressive decrease in density (or increase in porosity) a significant initial increase in strength with increased fibre content occurred over the range 5% to a maximum at 15% fibre mass fraction (Figure 1a, curve I). This observation is valid for sheets produced without additional pressure applied to the sheet after production.
c. Increased pressure applied to the 'green sheet' results (unsurprisingly) in increased density (Figure 1b) and a corresponding increase in modulus of rupture (Figure 1a).
d. Similar trends of the influence of fibre mass fraction are reproduced with increasing pressure, although an interesting shift in the maximum value occurred towards greater fibre contents for applied pressures of 6107 kPa (i.e. from 15% to 20% fibre mass fractions).

Interpretation of these results is a complex assignment since an increase in fibre content results in a simultanuous increase in both fibre–cement ratio and porosity. The former variable theoretically achieves an optimum when the cement specific surface area is insufficient to

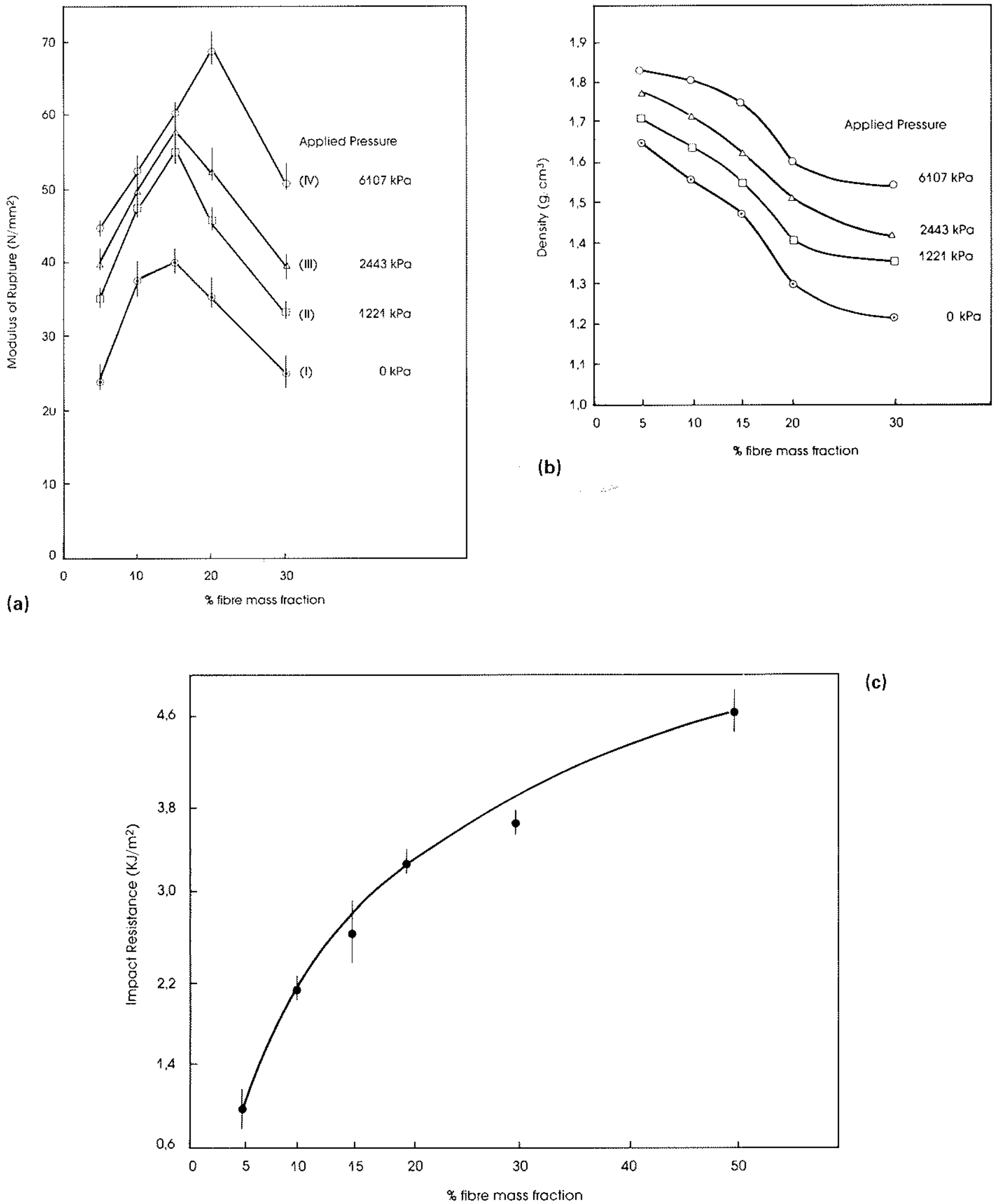


Figure 1 Influence of fibre content on (a) modulus of rupture, (b) density, and (c) toughness, at varied applied pressures. Processing parameters held constant were: collering (20 min.); fiberising (1 min.); Rapid hardening portland cement (4000 cm^2/g)

provide complete coverage to all the fibres, while the latter tends to reduce the strength. In order to compensate for the increased porosity, pressure may be applied to the green sheet. This treatment leads to an expulsion of pore water which in turn reduces the water–cement ratio of the sheet. This obviously has an influence on the hydration reaction of the matrix and the interfacial bond, resulting in strength and toughness variations. Considering these inter-related phenomena, the drop-off in strength (curve I, Figure 1a) at fibre mass fractions greater than 15% may initially be assigned to either:
1. the optimum fibre–cement ratio achieved; and/or
2. the influence of porosity; and/or
3. the optimum water–cement ratio.

The first scenario here, however, may be ruled out since a pressure applied to the green sheet results in an increase in strength at fibre mass fractions of 15%. In fact this is confirmed by the shift in the maximum value towards greater fibre contents for applied pressures of 6107 kPa (Figure 1a).

It is reasonable, therefore, to assume that the drop in strength observed, after the maximum value has been achieved, with increased fibre contents, is rather governed by the influence of porosity and water–cement ratio. Also, the increase in strength for the range of fibre mass fractions 5% to 15% in the case of non-compressed products is dominated largely by the fibre volume contribution despite the porosity increase.

It is interesting to note that, regardless of changes in porosity and water–cement ratio, the increase in impact resistance (Figure 1c) is dominated significantly by the increase in fibre content.

Considering compressed products (for applied pressures of 1221, 2443 and 6107 kPa) the arguments proposed previously are also valid except for curve IV (Figure 1a) where the maximum strength value has shifted, as previously mentioned. For practical reasons the pressure was not increased to values greater than 6107 kPa; however, it is reasonable to assume that the maximum value achievable could be shifted even further towards higher fibre contents with pressures in excess of 6107 kPa.

On the other hand if, for example, the fibre content were kept constant and the applied pressure increased progressively it is logical to assume that an optimum water–cement ratio should be achieved. In the light of this argument, consider Figure 1a which represents a decrease in measured water–cement ratio with increased applied pressures for a constant fibre mass fraction (15%).

The decrease in water–cement ratio should effectively result in changes in the mechanical properties of the composite as the hydration reaction would certainly be influenced by a reduction in the amount of water present [2, 3].

In order to study further the influence of water–cement ratios on strength and toughness of asbestos cement a second series of experiments was therefore conducted. Here the mix proportions were held constant and a processing technique (specifically, the filtration rate), on the Hatschek machine was adjusted to vary the water–cement ratio. (As it was not physically possible to produce sheets with varying water–cement ratios at constant porosity, this variable must also be taken into account.)

The corresponding results, shown in Figures 2a, b and c, indicate that an increase in strength and toughness occurred with decreasing water–cement ratio and porosity. This achieved a maximum value at a water–cement ratio of approximately 0.33, followed by a subsequent drop in strength and toughness with further decreases in water–cement ratio.

It is reasonable to assume that the initial increase in strength and toughness with decreased water–cement ratios may be associated with a decrease in porosity, and the subsequent drop-off at values less than 0.33 may be assigned to incomplete hydration due to lack of water.

Collering, fiberisation and density

Chrysotile asbestos fibres delivered for asbestos cement production consist of fibre bundles having a large spectrum of lengths and diameters which is entirely dependent on the quality of the delivery. For example, lengths can vary from micro-dust particles to around 6 mm, with diameters from 0.1 μm to 50 μm.

Prior to the addition of these fibres to the cement slurry in the Hatschek process, mechanical collering and a fiberising process are first carried out. As mentioned, this results in splitting or opening up of the fibre bundles. An optimum degree of collering and fiberisation is required in order to achieve the maximum mechanical property potential from the composite, so that this is of obvious economic interest to the asbestos cement industry. The degree of collering and fiberisation, and associated changes in density, have therefore been examined in some detail, in conjunction with their influence on the strength and toughness of the composite, and the following discussion reports on the results obtained.

Using mixes with a specified fibre content and cement fineness, sheets were manufactured using three collering times (20, 40 and 60 minutes) and two extreme fiberising times (1 and 60 minutes spinning). Corresponding variations found in strength, toughness and density are given in Figures 3a, 3b and 3c for the above mentioned experimental programme. From these results it may be shown that a progressive increase in collering followed by a relatively short fiberisation time (1 minute) resulted in a progressive increase in both strength and impact resistance. Exactly the opposite effect occurred for the same variation of collering time but where this was followed by a relatively long fiberising treatment, involving 60 minutes spinning.

It is of interest to note that the combination of 20 minutes collering and 60 minutes fiberisation resulted in equivalent or possibly marginally higher strength values (although lower toughness) when compared with the combination of 20 minutes collering and 1 minute fiberisation. This would imply that fiberisation beyond a certain limit (1 minute spinning) does not significantly improve the composite mechanical performance. On the

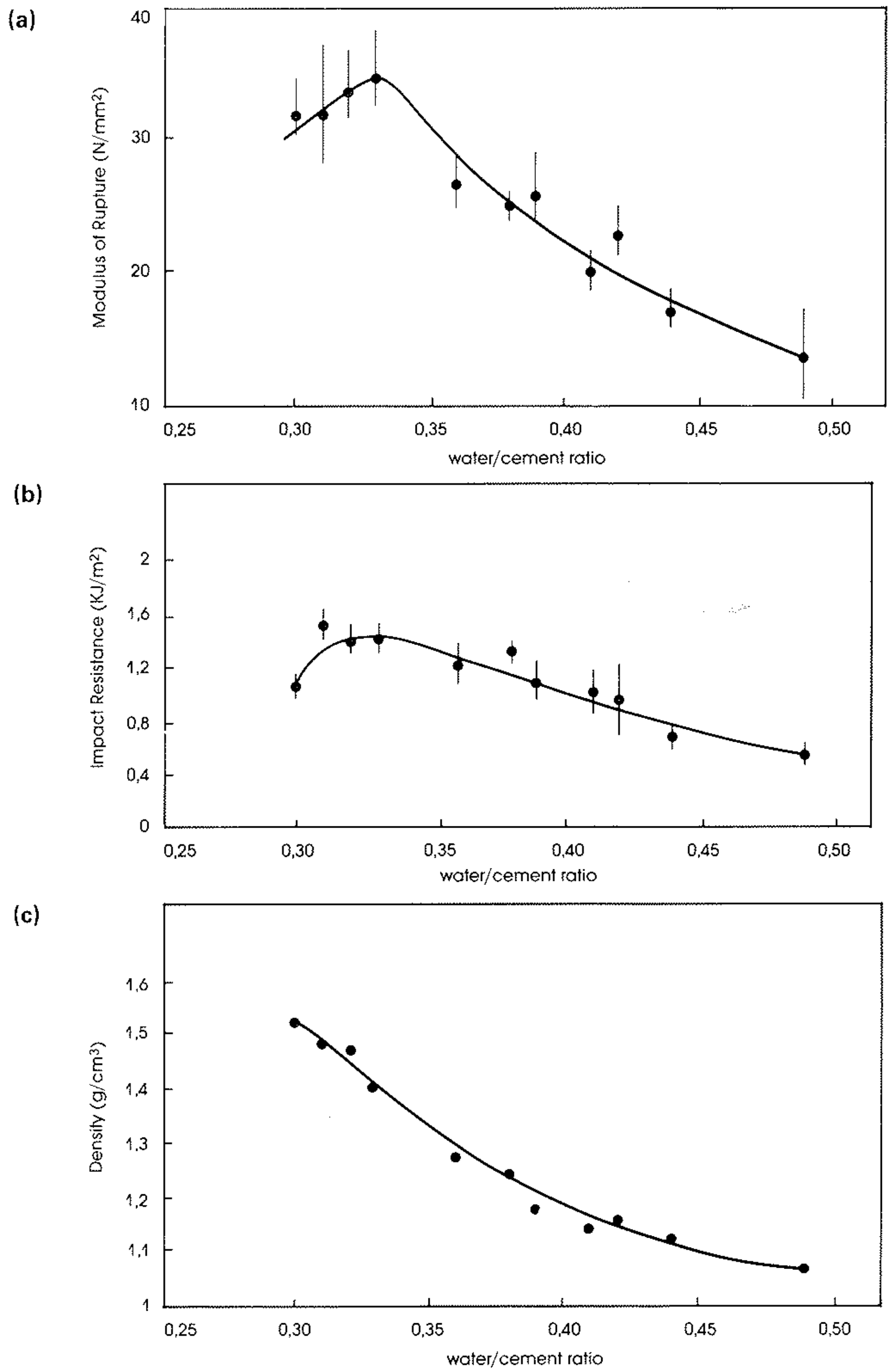


Figure 2 Influence of water–cement ratio on (a) strength (b) toughness, (c) density. Processing parameters held constant were: collering (20 min.); fiberising (1 min.); fibre mass fraction (12%); RHPC

other hand, keeping relatively short fiberising times and increasing collering times from 20 to 60 minutes resulted in increases of 28% in strength and 26% in toughness. Such improvements are certainly significant enough to be considered of economic interest.

It is also interesting to see that progressive increases in collering with products having short fiberisation times show a marginal density increase; those with long fiberisation times, however, displayed a significant drop in density (Figure 3c). This result may be explained by means of the two differing mechanical opening treatments taking place, i.e. the grinding or

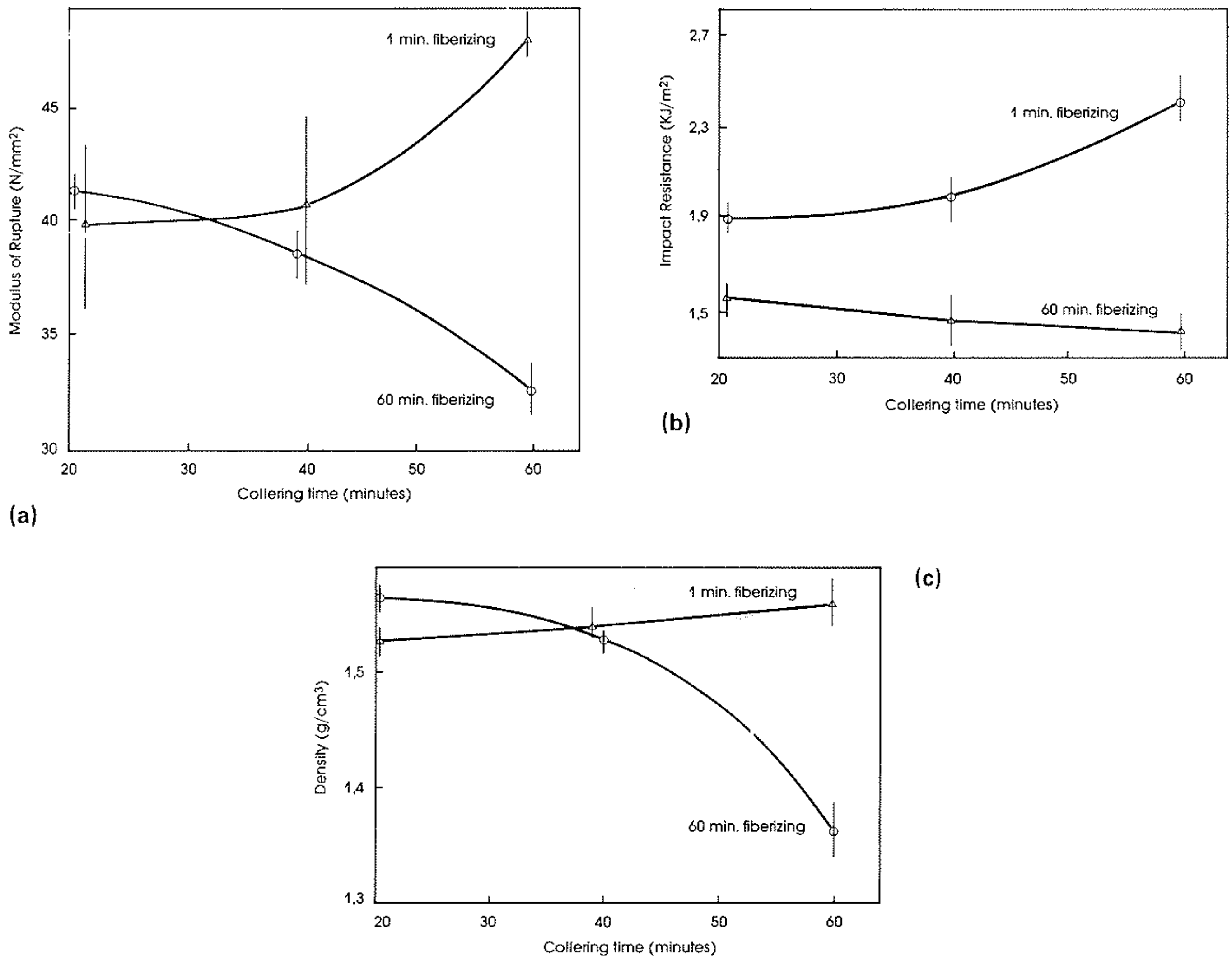


Figure 3 Influence of collering and fiberising on (a) strength, (b) toughness, and (c) density. Processing parameters held constant were: fibre mass fraction (12%); RHPC

milling collering process compared with the 'fluffing' action of the fiberiser. Thus the fluffing action of the fiberiser leads to a greater water retention of the liquid suspension compared with the collering process. This has an obvious influence on the filterability of the cement slurry and leads to higher water–cement ratios and higher porosities in the Hatschek process.

Cement fineness, fiberisation and density

Asbestos fibre pretreatment results in an increase in the specific surface area of the fibre mass influencing, correspondingly, the cement surface coverage during the production process. It is of obvious importance, then, to investigate the influence of cement surface coverage and fibre specific surface area, as they relate to the mechanical properties of the composite.

An investigation was conducted using two fibre pretreatments:

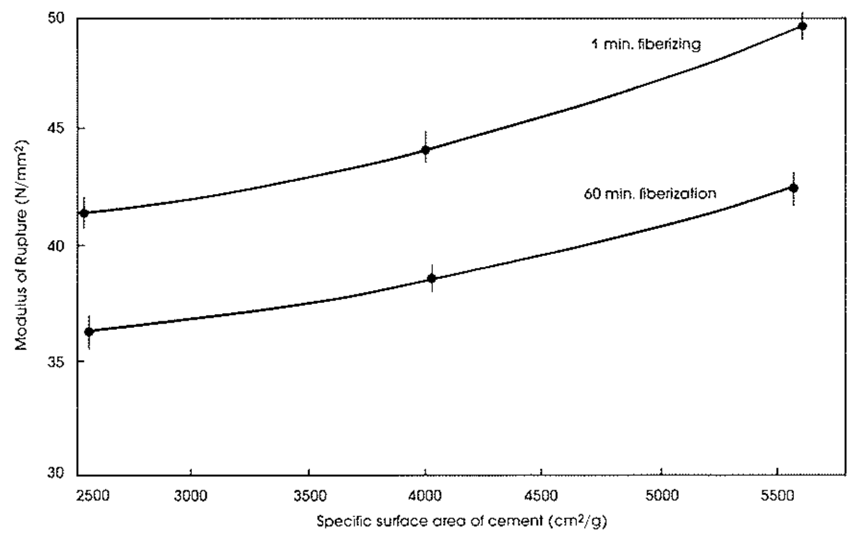
a. 60 minutes collering, 1 minute fiberisation; and
b. 60 minutes collering, 60 minutes fiberisation.

Composite sheets were prepared using these pretreatments with three cement specific surface areas, viz: Blaine values of 2500, 4100 and 5500 cm^2/g. The results given in Figures 4a, 4b and 4c show the corresponding effect on the strength and toughness of the resulting composite.

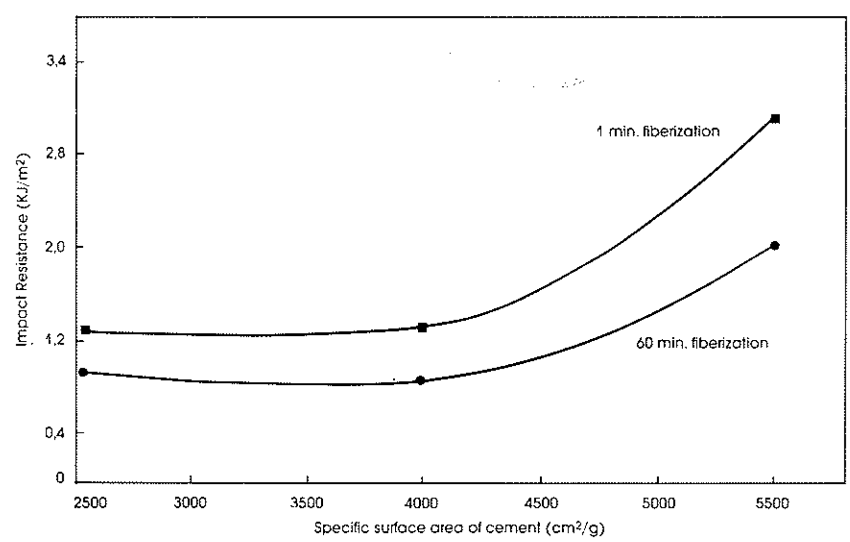
It is well known that cements of increasing fineness achieve equivalent strength levels at reduced curing times. For this reason all results given in Figures 4a, 4b and 4c represent test values obtained after 42 days curing, at which stage it is to be anticipated that strength will have reached a value which, subsequently, changes very little.

In general it was found that an increase in strength and toughness corresponded with an increase in cement specific surface area for both fibre pretreatments studied (Figures 4a and 4b), despite the corresponding change in

(a)



(b)



(c)

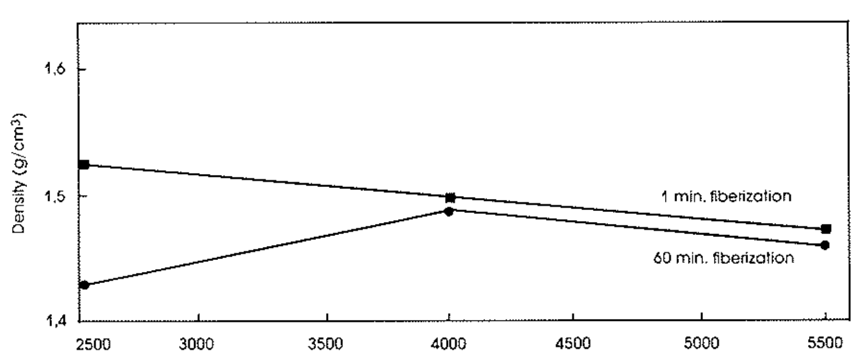


Figure 4 Influence of cement specific surface area on (a) strength, (b) toughness, and (c) density for two particular fibre pretreatments. Processing parameters held constant were: collering time (20 min.); fibre mass fraction (12%). (Note: specimens were tested after 42 days curing.)

density (Figure 4c). Thus it may be assumed that the potentially negative influence of density on mechanical properties is dominated by an increase in cement specific surface area which improves the fibre surface coverage and interfacial contact.

When comparing the properties of composites made with the two different fibre pretreatments, both show similar trends but at two distinct strength levels, consistent with results described in the preceding section.

Overall, therefore, it would appear that in order to achieve maximum strength and toughness from an asbestos cement composite material long collering times, short fiberising times and as fine a cement as practically (and economically) possible are to be recommended.

CONCLUSIONS

1. An increase in fibre mass fraction (M_f) for Mini-Hatschek tests resulted in an increase in strength which achieved a maximum at 15% M_f followed by a subsequent drop in strength with further increase in fibre content. It is suggested that the increase in strength to 15% M_f is due to the increase in fibre reinforcement and the subsequent drop in strength can be associated with an overriding effect of porosity (decrease in density.)

2. A corresponding progressive increase in impact resistance can be directly related to an increase in fibre content, irrespective of porosity variations. It seems reasonable to suppose that since fibre pull-out is the dominant mechanism governing impact resistance, the increase in fibre content results in increased fibre pull-out with a corresponding increase in impact resistance.

3. A progressive increase in the pressure applied to an asbestos cement sheet immediately after manufacture results in an increase in strength. The relative position of the upper strength limit with respect to applied pressure is dependent on the fibre content. It is suggested that this increase in strength is due to:

a. a decrease in porosity and therefore a decrease in the number of voids which act as crack initiators; and
b. a decrease in water–cement ratio.

4. An optimum water–cement ratio of 0.33 was found for the Mini-Hatschek specimens studied. It is suggested that the observed decrease in strength and impact resistance with:

a. increasing water–cement ratio above 0.33 is due to the introduction of voids which act as crack initiators; and
b. decreasing water–cement ratios below 0.33 is probably due to insufficient water at the fibre–cement interface for complete hydration to occur.

5. In regard to the influence of fibre pretreatment for the range examined, long (60 minutes) collering followed by short (1 minute) fiberisation produced the optimum strength and impact resistance achieved for asbestos cement sheets made on the Mini-Hatschek. Longer spinning (more opened fibres) implies greater water retention, with corresponding increased water–cement ratio and porosity and reduced strength and toughness.

6. The strength and impact resistance was generally found to increase with increasing cement specific surface area. This effect seems to be due to a stronger interfacial bond which could develop further with the finer cements as a result of increased interfacial contact.

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