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**2012-09**
Elsevier
http://hdl.handle.net/10539/21460
Asumani, O. M. L., Reid, R. G. and Paskaramoorthy, R. 2012. The effects of alkali-silane treatment on the tensile and flexural properties of short fibre non-woven kenaf reinforced polypropylene composites. Composites Part A: Applied Science and Manufacturing 43(9), pp. 1431-1440. DOI: 10.1016/j.compositesa.2012.04.007

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# The effects of alkali-silane treatment on the tensile and flexural properties of short fibre non-woven kenaf reinforced polypropylene composites

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## ABSTRACT

Kenaf fibre reinforced polypropylene composites were manufactured by compression moulding. The kenaf fibre was considered in three forms; untreated, treated with sodium hydroxide solution and treated with sodium hydroxide solution followed by three-aminopropyltriethoxysilane. The effects of these chemical treatments on the tensile and flexural properties of the composites were investigated. Mechanical test results show that alkali treatment followed by three–aminopropyltriethoxysilane treatment (alkali–silane treatment) significantly improves the tensile and flexural properties of short fibre non-woven kenaf polypropylene composites. In particular, the specific tensile and flexural strengths of alkali–silane treated kenaf composites with 30% fibre mass fraction are, respectively, only 4% and 11% lower than those of composites made using glass fibre. Scanning electron microscopy examination shows that the improvements in the tensile and flexural properties resulting from alkali–silane treatment can be attributed to better bonding between the fibres and matrix.

***Keywords***:
*Kenaf fibre*

*B. Fibre/matrix bond*

*C. Mechanical testing*

*E. Surface treatment*

## 1. INTRODUCTION

Natural fibres are increasingly being considered as an environmentally friendly substitute for synthetic fibres in the reinforcement of polymer based composites [1–7]. The use of these fibres instead of glass and carbon is, for example, under consideration in the transportation industry [7]. Although many different types of natural fibres are available, kenaf (*Hibiscus cannabinus*) is a particularly attractive option due to its rapid growth over a wide range of climatic conditions [8] and its consequent low cost [7]. Although the use of natural fibres partly satisfies the requirements of regulations that enforce the use of environmentally friendly and sustainable materials [9], the matrix system must also be considered in this regard. Clearly, completely biodegradable materials such as polylactic acid (PLA) are preferable, but the current high cost of these materials is a disadvantage in comparison to polypropylene (PP) which has a low cost and is easy recycled [10,11]. Kenaf/PP composites are therefore of considerable commercial interest.

Even though natural fibres have the potential to supplement glass fibres in polymer composites [12, 13], limitations arise with respect to mechanical performance and moisture absorption when natural fibres are used [14,15]. These limitations are present irrespective of whether thermoset or thermoplastic polymers are used as the matrix material. Previous studies [4, 16] have reported that the main factor that limits the mechanical properties of natural fibre reinforced thermoplastic composites is the chemical incompatibility between the hydrophilic lignocellulosic molecules of the natural fibre and the hydrophobic thermoplastic molecules. This incompatibility leads to difficulties in ensuring effective fibre–matrix interface bonding which, in turn, causes ineffective load transfer between the reinforcing material and matrix. Various options, including chemical treatments of lignocellulosic fibres and the use of compatibilizers, have been suggested in order to achieve the necessary compatibility of surface energies

between the fibre and matrix. Li et al. [13] presented a review article on the various chemical treatments used to improve the compatibility between lignocellulosic fibres and polymer matrices. Approaches such as alkali treatment, silane treatment, acetylation, benzoylation, use of maleated coupling agents, peroxide treatment, permanganate treatment, and isocyanate treatment were considered. Amongst the various methods presented, alkaline and silane treatments have been widely reported.

Alkaline treatment involves immersing the fibres in an alkaline solution, frequently that of NaOH, for a period of time. It is believed to work by increasing the surface roughness of the fibre which improves the mechanical bonding [13]. It also exposes more cellulose on the surface of the fibre to potential chemical bonding with the matrix material [13]. Van de Weyenburg et al. [17] reported up to 30% increases in the tensile strength and modulus of flax reinforced epoxy composite. Edeerozey et al. [14], considered the effects of alkaline treatment on kenaf fibre. It was found that alkaline treatment with an NaOH solution of 6% strength was effective at cleaning the fibre surface. Increasing the solution strength further to 9%, on the other hand, appears to have damaged the fibres, and thereby reduced their strength.

Silane treatment usually entails soaking the fibres in a weak solution of a silane diluted in a water/alcohol or water/ketone mixture. In the presence of water, silane breaks down into silanol and alcohol. The silanol reacts with the OH groups of the cellulose in natural fibres, forming stable covalent bonds to the cell walls that are chemisorbed onto the fibre surface [18]. Use of silane improves the degree of cross-linking in the interface region and increases the fibre surface area, allowing for stronger bonding between the fibre and matrix [19]. Van de Weyenburg et al. [17] soaked flax fibres for 2 h in a 1% solution of 3-aminopropyltrimethoxy silane (APS) diluted in a 50/50 mixture of acetone and water. When the dried fibres were used to reinforce epoxy at a volume fraction of 40%, the tensile modulus increased by approximately 45% compared to the composite of untreated fibres. The strength, however, improved by only about 4%. Lee et al. [20] considered kenaf fibres in a PLA matrix. In this case, 3-glycidoxypropyl trimethoxy silane (GPS) was used to treat the fibres. It was seen that only a small concentration of silane (1%) was required to increase the flexural strength and stiffness of a composite of 50% mass fraction by approximately 20% and 25%, respectively, when compared against

the untreated kenaf/PLA composite. Cho et al. [8] considered kenaf fibres as reinforcement for PP and polyester. Three different silanes were considered; APS, GPS and 3-methacryloxypropyltrimethoxy silane (MPS). It was found that GPS was the most effective treatment when applied at a concentration of 0.5% by mass. Using this treatment, the flexural and tensile strengths increased relative to those of the composite made from untreated fibre by 26% and 17%, respectively. The corresponding increases in the moduli were about 8% and 20%.

While most researchers have used either alkali or silane treatments, it also makes sense to use them in combination, since the mechanisms whereby they operate on the natural fibres are completely different. Herrera-Franco and Valadez-González [4] considered high density polyethylene (HDPE) reinforced with henequén fibres at a volume fraction of 20%. The effects of alkali and silane treatments on these fibres were studied individually in addition to the effect of the two treatments acting in combination. Silane treatment made use of vinyltris (2-methoxy-ethoxy) silane. When tensile strength was considered, it was found that alkali treatment resulted in almost no improvement, whereas silane treatment resulted in a 19% improvement. When the combination of treatments was considered, the tensile strength increased by 30%. The improvement in flexural strength with fibre treatment followed the same trend as that of tensile strength although to a lesser degree. The trend in results was, however, reversed when tensile modulus was considered. While the alkali treatment provided about 10% improvement, the combined treatment reduced the tensile modulus. Sgriccia et al. [15] considered a variety of fibres, including kenaf, to reinforce epoxy. Flexural modulus was presented for untreated fibres, fibres subjected to alkali treatment, fibres subjected to silane (GPS) treatment and fibres given the combined treatment. No significant trend dependent on fibre treatment is apparent in these results. Huda et al. [19] considered PLA reinforced with kenaf fibre. They, too, considered the effects of alkali treatment, silane treatment and the combination of these two approaches. The silane used in this work was APS. For composites of 40% fibre mass fraction, the improvements in strength were in the region of 30%, 50% and 60% compared to the composite of untreated fibres for the alkali, silane and combined treatments, respectively. Irrespective of the surface treatment however, the flexural strength of the composites was lower than that of the unreinforced matrix

material. The composite of untreated fibres was about 65% stiffer than PLA. The stiffness was increased still further, by 48%, 69% and 80% respectively, using alkali treatment, silane treatment and the combined treatment.

The effects of combined alkali and silane treatments on the tensile and flexural properties of short fibre non–woven kenaf reinforced polypropylene composites are investigated in the present study. The fabrication method of compression moulding was optimised to reduce the processing time and heat, thereby preventing alteration of the crystalline structure of the matrix system and thermal degradation of the kenaf fibre. For comparison purposes, composites reinforced by E-glass fibre in the form of chopped strand mat were also manufactured using the same process. The present work is an extension of that done by Cho et al. [8] who considered the effect of silane treatment of kenaf fibres in a polypropylene matrix, but who did not consider the effects of the combined alkali-silane treatment. The present work is also inspired by that of Herrera-Franco and Valadez-González [4] and Huda et al. [19] who investigated the combined treatment on other fibre/matrix systems. When the results of these investigations are considered together in detail, they are somewhat contradictory, but nonetheless imply that the combined treatment could improve the tensile and flexural strengths of the composite in comparison to silane or alkali treatment alone. Given the low cost of kenaf and PP, and the potential improvements to be obtained by using the alkali-silane treatment in the manufacture of a kenaf/PP composite, this study has clear economic implications.

## 2. **EXPERIMENTAL METHOD**

### 2.1 Materials

Non-woven kenaf fibre mats of 125 g/m$^2$ and 350 g/m$^2$ areal density were donated by Sustainable Fibre Solutions of South Africa. The lengths of kenaf fibre within the mat were found to vary between 5.0 mm and 22.4 mm with an average of 14.0±0.5 mm. E-glass chopped strand mat of 125 g/m$^2$ was obtained from Owens Corning. Polypropylene-homopolymer in the forms of sheet and microfine powder was obtained from Sasol.

Perfluoroalkoxy (PFA) sheets used as a release agent were donated by Fibre-Wound. The mechanical properties of kenaf fibre, glass fibre and polypropylene are shown in Table 1.

## 2.2 Chemical treatment of kenaf fibres

Sodium hydroxide (NaOH) solutions with concentrations ranging from 1% to 8% in intervals of 1% by mass were used for the alkali treatment. Kenaf fibre mats were immersed in the NaOH solution for 24 hours at a temperature of 45ºC. After immersion, the mats were washed with running tap water and then immersed in distilled water containing 1% acetic acid to neutralize the remaining NaOH molecules. These mats were then dried in an oven at 45°C for a period of 12 hours. This was followed by a silane treatment as follows: 5% by weight of three–aminopropyltriethoxysilane (weight of silane relative to the weight of kenaf mat) was diluted in a 50% aqueous solution of methanol. The pH of the solution was maintained between 4 and 5 using acetic acid. The mats were immersed in the solution for 4 hours at a temperature of 28 ºC and then washed with distilled water before being dried in the oven at 45°C for 12 hours.

## 2.3 Fabrication of composite plates

The compression moulding technique was used to fabricate kenaf and glass fibre reinforced PP composites. The PP was in the form of microfine powder and sheets. The use of microfine powder in the compression moulding process has been shown [1] to be the optimal fabrication method for this combination of materials. The manufacturing process comprised five stages, namely; compaction, fibre impregnation, compression, release of the compaction load and cooling. The first step was to make the material charge by sandwiching kenaf mat impregnated with polypropylene powder between polypropylene sheets. The quantity of polypropylene powder was calculated to achieve the desired fibre content for each composite. The general manufacturing arrangement is illustrated in Fig. 1. The material charge was then loaded into the mould cavity. The mould, a detailed view of which is shown in Fig. 2, was fabricated from steel plate. Thin PFA sheets of 0.2 mm thickness were used as a release agent to allow a smooth finish on

the surface of the composite plates. The closed mould was then loaded into the oven and subjected to a compressive load equivalent to a pressure of 75 bar for 15 minutes to compact the material charge. The temperature of the oven was increased and stabilized at 250°C for a period of 35 minutes to lower the viscosity of the matrix system allowing the polypropylene to impregnate into the fibres. The compressive load was then reduced and maintained at 50 bar for a period of 15 minutes to prevent resin flash and to minimize uneven fibre distribution. The temperature in the oven and the compressive load were then gradually decreased to ambient and 5 bar respectively, over 5 minutes. This prevented the formation of voids. The closed mould was allowed to cool under a compressive load of 5 bar for 20 minutes to inhibit geometrical distortion of the composite plate. Finally, the fabricated plate was released from the mould at ambient temperature. The manufacturing parameters are presented in Table 2. A graphical illustration of the variation in process conditions is shown in Fig. 3. Temperatures presented in this figure were measured using K-type thermocouples. Temperatures of the mould and composite plate were determined by placing thermocouple junctions on the inner surface of the mould and within the material charge, respectively.

## 2.4 Material Characterization

Five different configurations of kenaf/PP composites were manufactured. These were unreinforced PP, PP reinforced with untreated kenaf fibre, PP reinforced with alkali treated kenaf fibre, PP reinforced with alkali–silane treated kenaf fibre and PP reinforced with E-glass.

Four different fibre mass fractions - 20%, 25%, 30% and 35% - were considered for both kenaf and glass fibre reinforced composites. Each fabricated composite plate was rectangular with dimensions of 90mm × 150mm. Depending on the fibre content, the thickness of the fabricated plates was found to range between 1.2 mm and 2.0 mm. Tensile tests and flexural tests were performed in accordance with the ISO 527 and ISO 178 standards respectively [25,26]. A Lloyd MX 100 universal testing machine equipped

with a 5 kN load cell was used for mechanical testing. A Zeiss EVO 40 scanning electron microscope was used for the microscopy studies.

## 3 RESULTS AND DISCUSSION

The effects that the different chemical treatments have on the tensile and flexural properties of the kenaf fibre reinforced composites are considered first. These results are then followed by a comparison between the specific tensile and flexural properties of kenaf and glass fibre reinforced composites. For all presented data, error bars correspond to one standard deviation.

### 3.1 Tensile strength

The variation in the tensile strength of composites manufactured with alkali treated fibres is presented in Fig. 4. It is evident that the tensile strength varies with alkali concentration and that, on average, the tensile strength of composites reinforced with alkali treated fibres improves over that of composites reinforced with untreated fibres. The improvements in properties are most noticeable for composites with 25% and 30% fibre content. The maximum value of the tensile strength is exhibited for fibres treated with a solution of NaOH at 5% concentration. For this treatment, with a 30% fibre content, the increase in tensile strength relative to the untreated fibre composite is 25%. At an NaOH concentration of 6%, the strength drops marginally. As the alkali concentration goes above 6%, however, the tensile strength drops significantly, regardless of the fibre content of the composites. This finding is consistant with the results of Edeerozey et al. [14] who attributed the drop in strength to chemical degradation of the kenaf fibre. It is also worth noting that, for mass fractions of 25% and 30%, the tensile strength is higher than that of the base PP, irrespective of the degree of NaOH treatment.

The tensile strength of composites with fibres that were subjected to the additional silane treatment is presented in Fig. 5. It is clear that the additional silane treatment

results in a significant increase in strength over those of composites with both untreated fibres and with fibres treated with alkali solution only. The tensile strength begins to increase substantially at alkali concentrations of around 3% and reaches its maximum value at an alkali concentration of around 5% to 6%. This behaviour can be explained by considering the SEM micrographs presented in Figs. 6 and 7. The first of these images shows the considerable deposits of natural compounds such as hemicellulose, wax and lignin which are still present on the fibre surface after treatment with a 3% solution of NaOH. The second image shows the clean surface of the fibre after treatment with a 6% solution of NaOH. The deposits contribute to poor fibre–matrix interfacial bonding by decreasing the interfacial area of contact between the matrix and fibre. Poor fibre–matrix interfacial bonding is confirmed by the failure mode of alkali–silane treated composites using less than 3% NaOH. SEM micrographs, presented in Figs. 8 and 9, show that the failure of composites of 30% fibre content that were treated in a solution of only 2% NaOH before silane exposure is mainly characterized by fibre debonding and fibre pull–out, followed by matrix yielding. This failure mode is a clear indication of ineffective load transfer between the matrix and fibre. This behaviour is not evident in Fig. 10, which presents an SEM image of the failure surface of a composite of 30% fibre content that was treated in a solution of 6% NaOH before silane. It can be seen that fracture is predominately characterized by fibre breakage. Fig. 11 shows a closer view of another position on the same failure surface. In this figure, PP matrix can be seen adhering to the kenaf fibres subsequent to matrix failure. These observations indicate that the alkali–silane treatment produces strong bonds between the PP matrix and the kenaf fibre, provided that the fibres are free of surface deposits.

Fig. 5 also indicates that alkali–silane treatment using an NaOH solution of 7% or greater compromises the tensile strength of the composite. The drop in strength can be attributed to excess delignification which results in damaged fibres [27]. Fig. 12 shows clear evidence of fibre degradation caused by a solution of 8% NaOH.

The effect of fibre content on the tensile strength of the composites is also worth considering. Improvement in the strength is expected with increasing reinforcing material. Figs. 4 and 5 show that no matter the surface treatment, the strength of the composites improves with fibre content up to maximum at 30%. As the fibre content goes

above 30% however, the strength drops noticeably for both kenaf fibre and glass fibre reinforced composites. The decline can be attributed to voids resulting from of the lack of matrix material due to poor penetration of the matrix into the fibres. Evidence of the voids in composites of 35% fibre fraction is presented in Figs. 13 and 14. No evidence of voids could not be found in composites of 30% fibre fraction even though Figs. 8-10 and many more SEM images, which are not presented for the reason of brevity, were carefully examined,

A quantitative description of the relative merits of the different fibre treatments can be obtained by considering Figs. 4 and 5. It can be seen that the strongest composite material is that with 30% by mass of alkali-silane treated fibres that were treated with an alkali solution concentration of 5%. This laminate has an improvement in tensile strength of 75% relative to the composite with untreated fibre. The strength improvement of the laminate treated with 6% alkali solution is 72%. Both of these values are significantly better than the 17% reported by Cho et al. [8] for kenaf/PP composites where the fibres were treated with silane without prior alkali treatment. Additionally, in the present work, the strength of the composite of alkali-silane treated fibres with an alkali treatment strength of 6% is 59% greater than that of the composite with fibres subjected to the alkali treatment alone. It is consequently clear that the combined alkali-silane treatment significantly increases the tensile strength of composites in comparison to either alkali treatment or silane treatment alone.

### 3.2 Tensile modulus

The tensile modulus of composites with alkali treated fibres is presented in Fig. 15. The variation in the tensile modulus with alkali concentration is very similar to that of the tensile strength presented in Fig. 4. On average, the tensile modulus of composites reinforced with alkali treated fibres improves over that of composites with untreated fibres and is most noticeable for composites with 25% and 30% fibre content. The maximum value of the tensile modulus is exhibited for fibres treated with a solution of NaOH at 5% concentration. For a composite of 30% fibre content, this treatment gives an

increase in tensile modulus of 11% relative to that of the composite with untreated fibre. This improvement in the tensile modulus compares very well with that reported by Herrera-Franco and Valadez-González [4] who measured an approximately 10% improvement in tensile modulus even though they were considering a different fibre/matrix system. In a similar manner to that reported for tensile strength, at an NaOH concentration of 6% the modulus drops slightly before dropping noticeably at higher concentrations of NaOH due to fibre damage caused by excessive delignification [27]. It is also worth noting that, for a mass fraction of 30%, the tensile modulus is higher than that of the base PP for all NaOH solution concentrations.

The tensile modulus of composites with fibres subjected to the combined alkali-silane treatment is presented in Fig. 16. The variation in tensile modulus with alkali treatment concentration closely matches that of the tensile strength shown in Fig. 5. The tensile modulus of the composites with fibres subjected to alkali-silane treatment is significantly higher than that of the composites with both untreated fibres and fibres treated with alkali solution only. The increase in modulus associated with the combined alkali-silane treatment is attributed to improved bonding between the fibres and the matrix. Sufficient load transfer between the matrix and the fibres occurs for the higher modulus of the fibres to beneficially impact on the modulus of the composite. The rapid improvement in tensile modulus between alkali solution strengths of 3% to 6% strengthens the hypothesis that the benefits of silane treatment are only fully realized if deposits on the surface of the fibre are first completely removed. The maximum tensile modulus is reached at an NaOH solution strength of 6% whereupon the modulus drops markedly at higher solution concentrations. This behaviour is the same as that observed for the tensile strength.

It is expected that the tensile modulus increases with fibre content. Figs. 15 and 16 indicate that this trend is only clearly present for NaOH solution concentrations greater than 3% and less than about 7% to 8%. The lack of correlation between modulus and fibre content at lower NaOH concentrations is explained by considering the cleaning action of the NaOH solution. Solution concentrations of 3% and lower do not remove the surface deposits of natural compounds which prevent proper adhesion of the matrix to the fibres. The transfer of loads between the matrix and the fibres is consequently limited,

and an increase in fibre content does not translate into an increase in stiffness. Similarly, at higher NaOH concentrations, the relationship between modulus and fibre content also breaks down as consequence of poor adhesion between the fibres and matrix. In this case, however the poor bond probably results from damage to the fibres resulting from delignification [27]. For NaOH solution concentrations in the range of 4% to about 6% the modulus for both surface treatments increases with fibre content up to a maximum at 30% fibre content, whereupon the modulus drops appreciably at a fibre content of 35%. The distinct decrease in modulus matches that in the strength and can probably be attributed to the presence of voids in the composite.

It is apparent from Figs. 15 and 16 that the composite of 6% NaOH alkali-silane treated fibres at 30% by mass has the highest tensile modulus. This composite has a modulus that is 75% greater than the stiffest composite with alkali only treated fibres. It is also 94% stiffer than the composite of untreated fibre. This improvement is significantly better than the 20% reported by Cho et al. [8] for kenaf/PP composites where the fibres were treated with silane without prior alkali treatment. The use of the combined alkali-silane treatment therefore significantly improves the tensile modulus of PP/kenaf composites in comparison to either alkali or silane treatment on their own.

### 3.3 Flexural strength

Flexural test results are presented in Figs. 17 and 18. It can be seen that the trends of the flexural strength values are similar to those of tensile strength. As was observed for tensile strength, the alkali-silane treated composites have a significantly higher flexural strength than the composites made with fibres treated with alkali solution only. The peak flexural strength occurs at an NaOH solution in the region of 5% to 6%. The increase in flexural strength corresponding to performing an additional silane treatment after the alkali treatment is in the region of 32%. The increase in strength associated with alkali-silane treatment in comparison to no fibre treatment at all is 50%. It is interesting that this trend in results is similar to that of Herrera-Franco and Valadez-González [4] who found that the flexural strength variation with fibre treatment mimicked that of the tensile strength but to a lesser degree. The flexural strength improvements associated with the

present alkali-silane treatment are significantly better than the 26% improvement of Cho et al. [8] who applied the silane treatment without a prior alkali treatment. It is therefore clear that the use of the combined alkali-silane treatment is a great deal more beneficial than either the alkali or silane treatment applied alone.

### 3.4 Specific properties

Test results show that 30% is the optimum fibre content for both kenaf and glass fibre reinforcement and 6% NaOH the optimum alkali concentration for alkali-silane treatment of kenaf fibres. For this reason, these parameters were used as the baseline for comparison between glass and kenaf reinforced composites. This comparison is presented in Fig. 19. It is clear that all the specific properties are significantly affected by the chemical treatment of the kenaf fibres. In every case the mechanical properties of PP composite reinforced with alkali–silane treated kenaf fibre are much better than those reinforced with untreated and alkali treated kenaf fibre. The improvement in the mechanical properties of the composite reinforced with alkali-silane treated fibre is so significant, in fact, that the specific tensile and flexural strengths rival those of glass fibre reinforced PP. The specific tensile strength of the kenaf/PP composite is 96% of that of the glass fibre composite. The corresponding value for specific flexural strength is 89%. The specific tensile modulus of this kenaf/PP composite also compares well with that of the glass composite at 82% of its value.

The good specific tensile and flexural properties of these short fibre non-woven kenaf/PP composites suggests that they could find application as substitutes to synthetic fibre composites in some applications.

## 4 CONCLUSIONS

Compression moulding was used to manufacture kenaf fibre reinforced polypropylene composites into sheet form. Mechanical test results and SEM examinations show that alkali treatment combined with three–aminopropyltriethoxysilane

treatment of kenaf fibres significantly improves the tensile and flexural properties of kenaf fibre reinforced polypropylene composites. The properties are considerably better than those obtained from either alkali or silane treatment alone. An NaOH concentration of 6% is the optimum for the alkali stage of the combined alkali-silane treatment. The specific tensile and flexural strengths of alkali–silane treated kenaf composites of 30% by mass compare extremely well to those of glass fibre composites.

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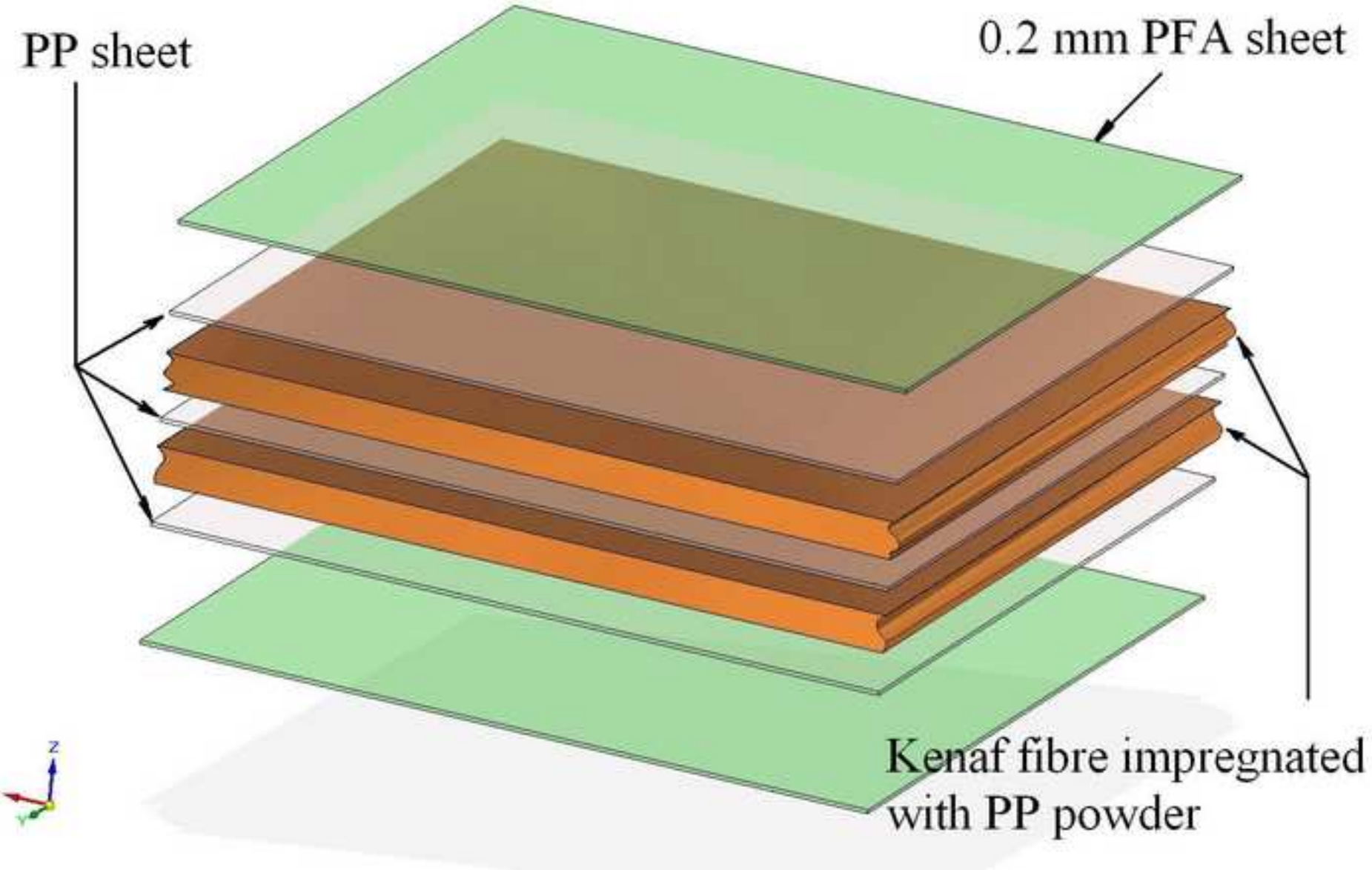
Fig. 18 Flexural strength of alkali–silane treated composites
Fig. 19 Specific mechanical properties of kenaf and glass reinforced PP composites


PP sheet
0.2 mm PFA sheet
Kenaf fibre impregnated
with PP powder
Z
X
Y

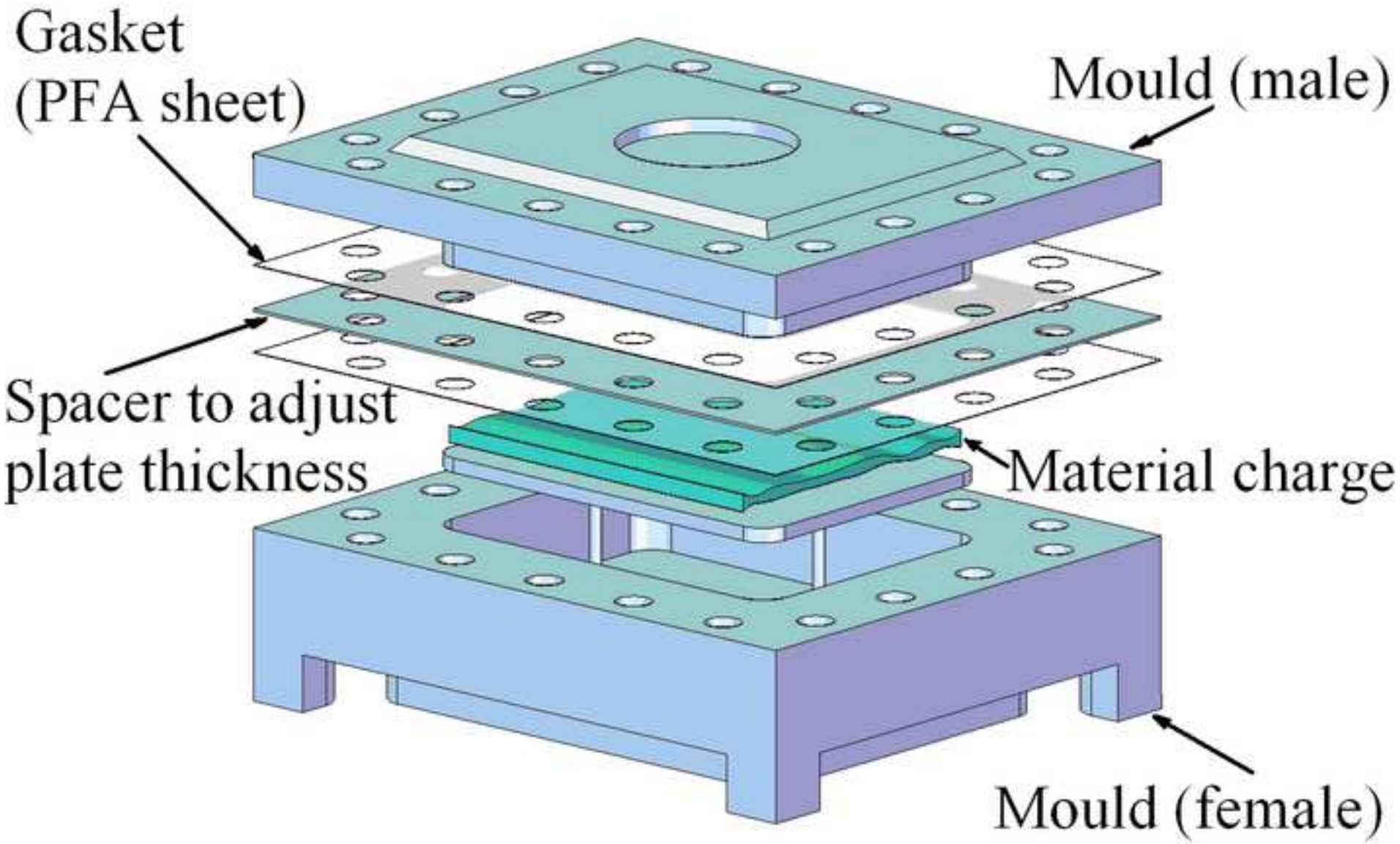

Gasket
(PFA sheet)
Mould (male)
Spacer to adjust
plate thickness
Material charge
Mould (female)

Fig. 3

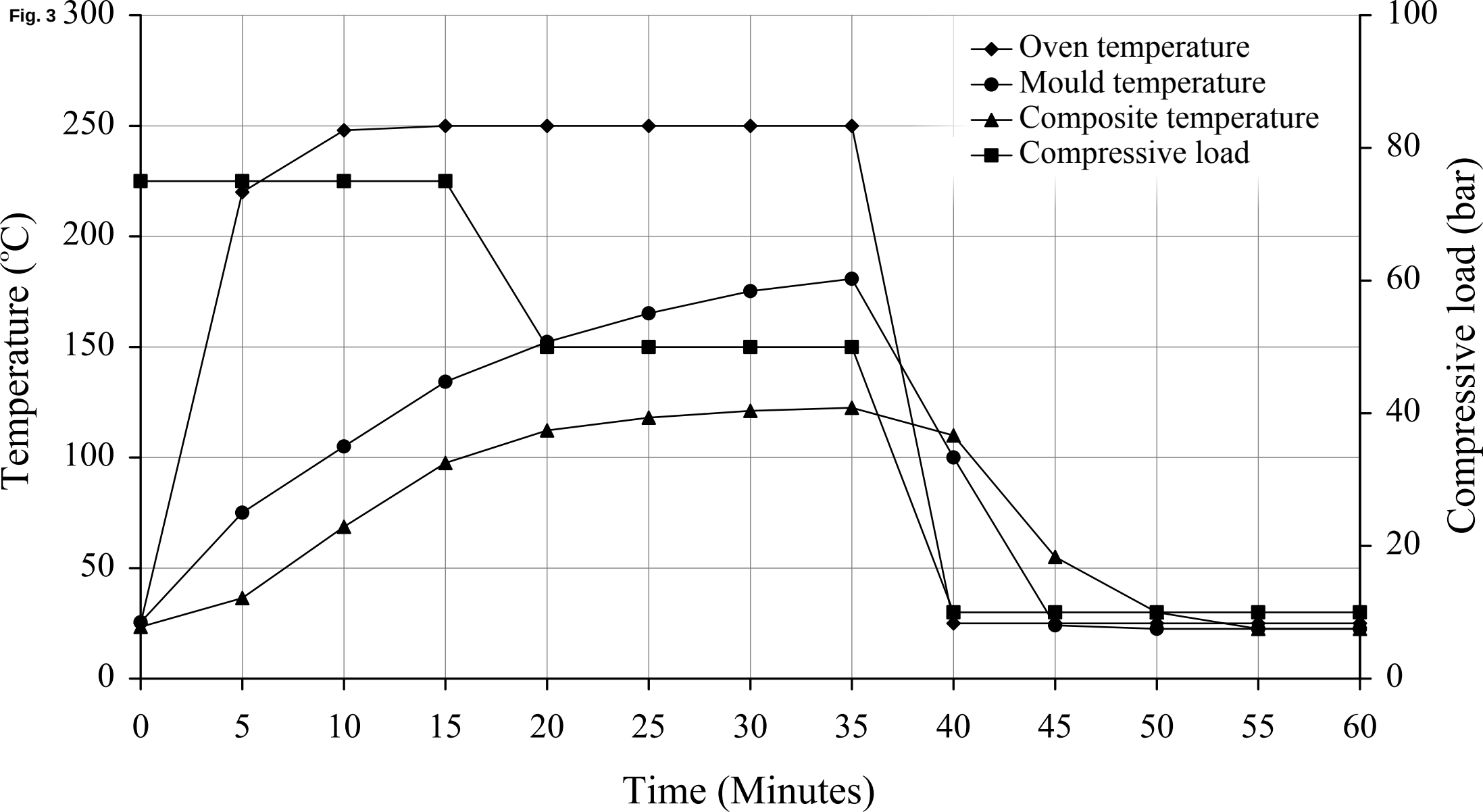

Oven temperature
Mould temperature
Composite temperature
Compressive load
Temperature (°C)
Compressive load (bar)
Time (Minutes)
0
50
100
150
200
250
300
0
20
40
60
80
100
0
5
10
15
20
25
30
35
40
45
50
55
60

Fig. 4

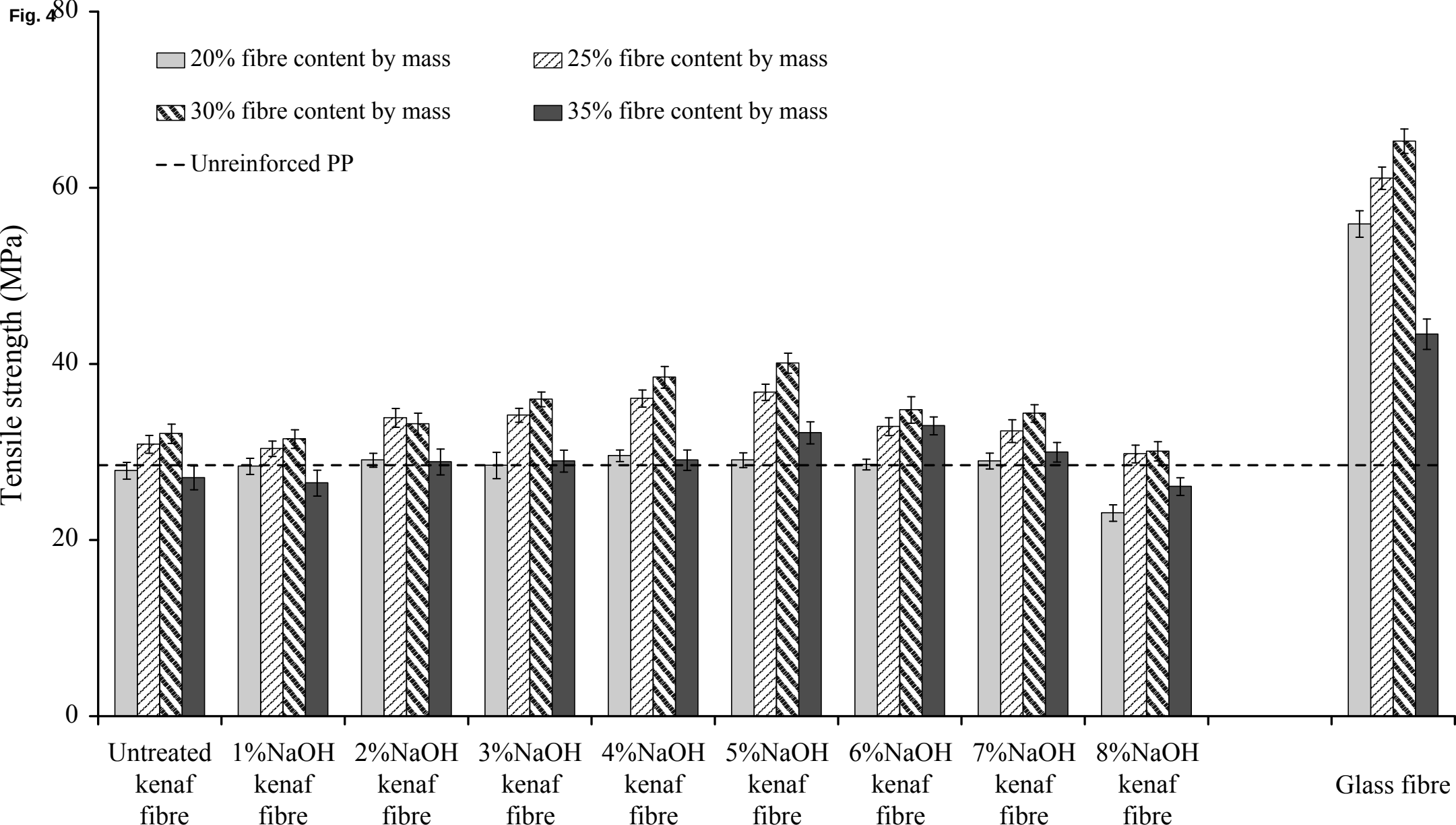
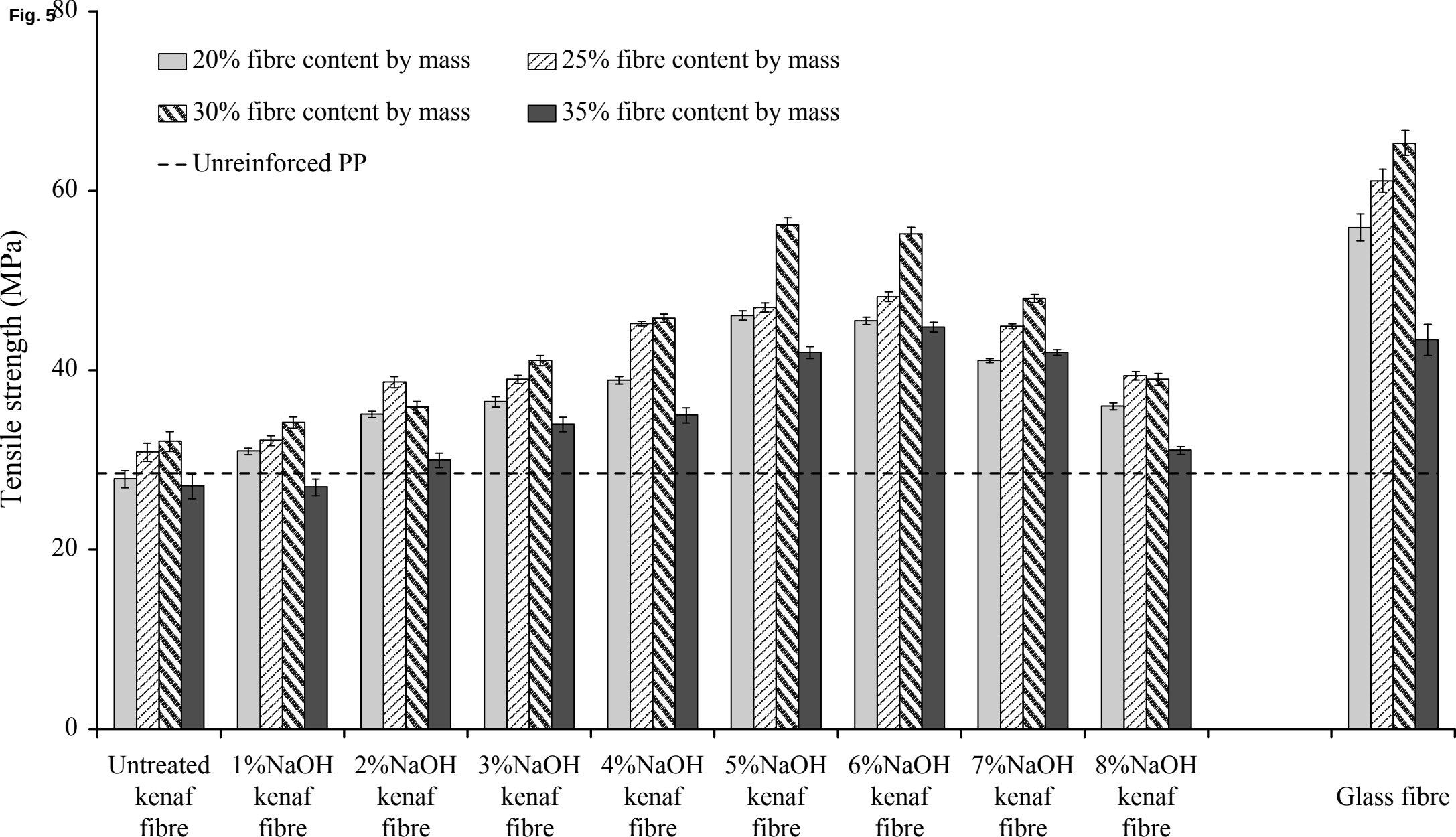
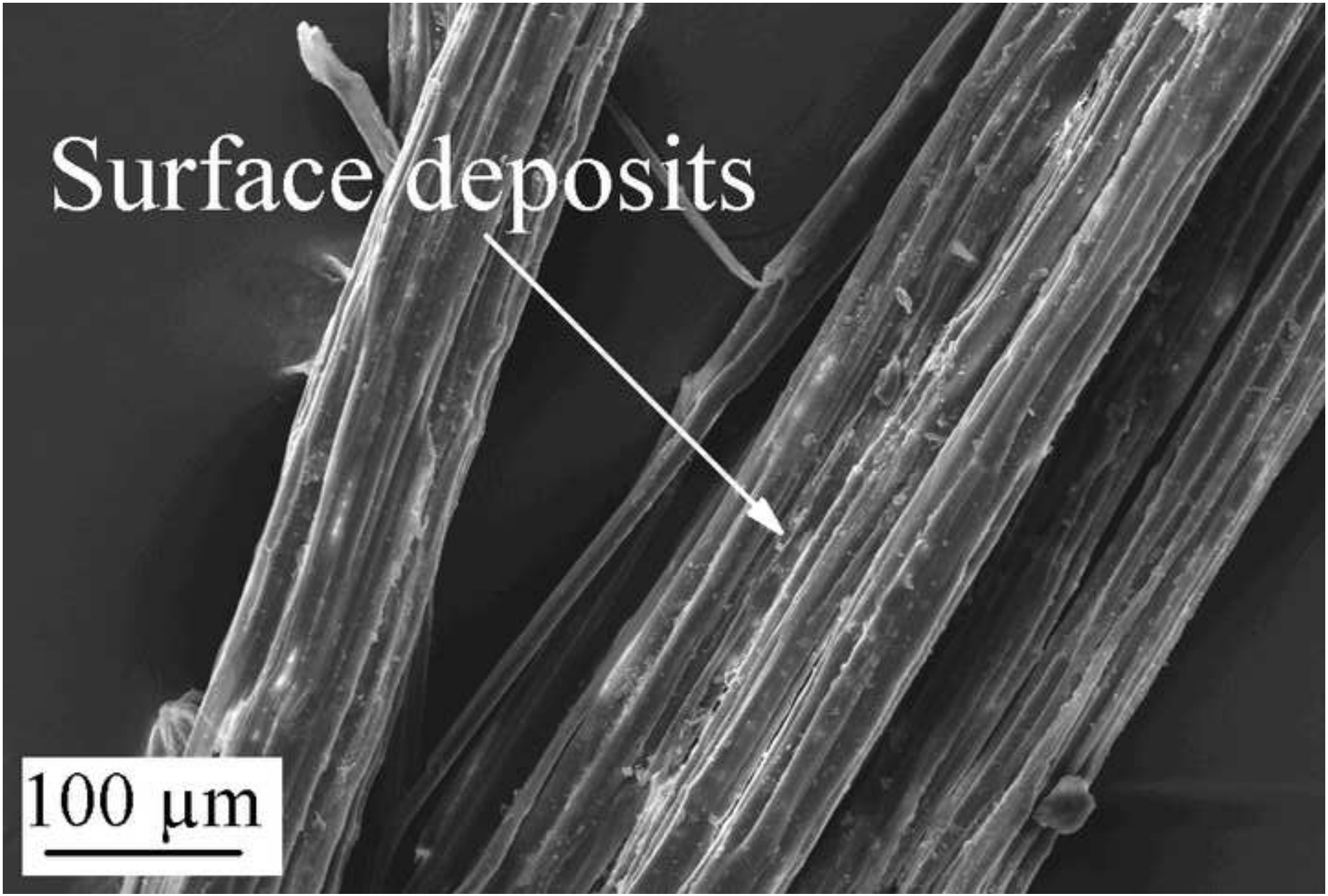
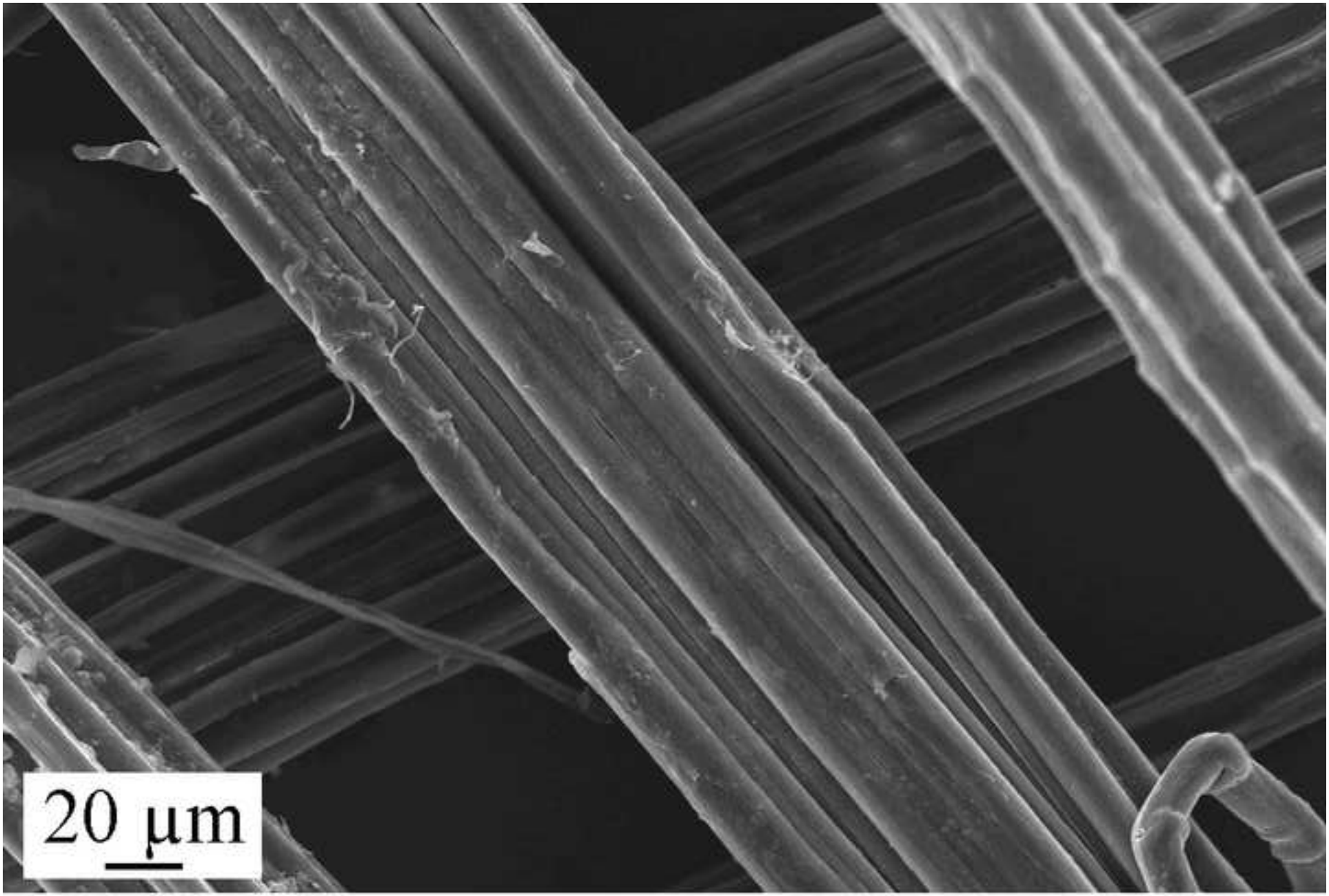
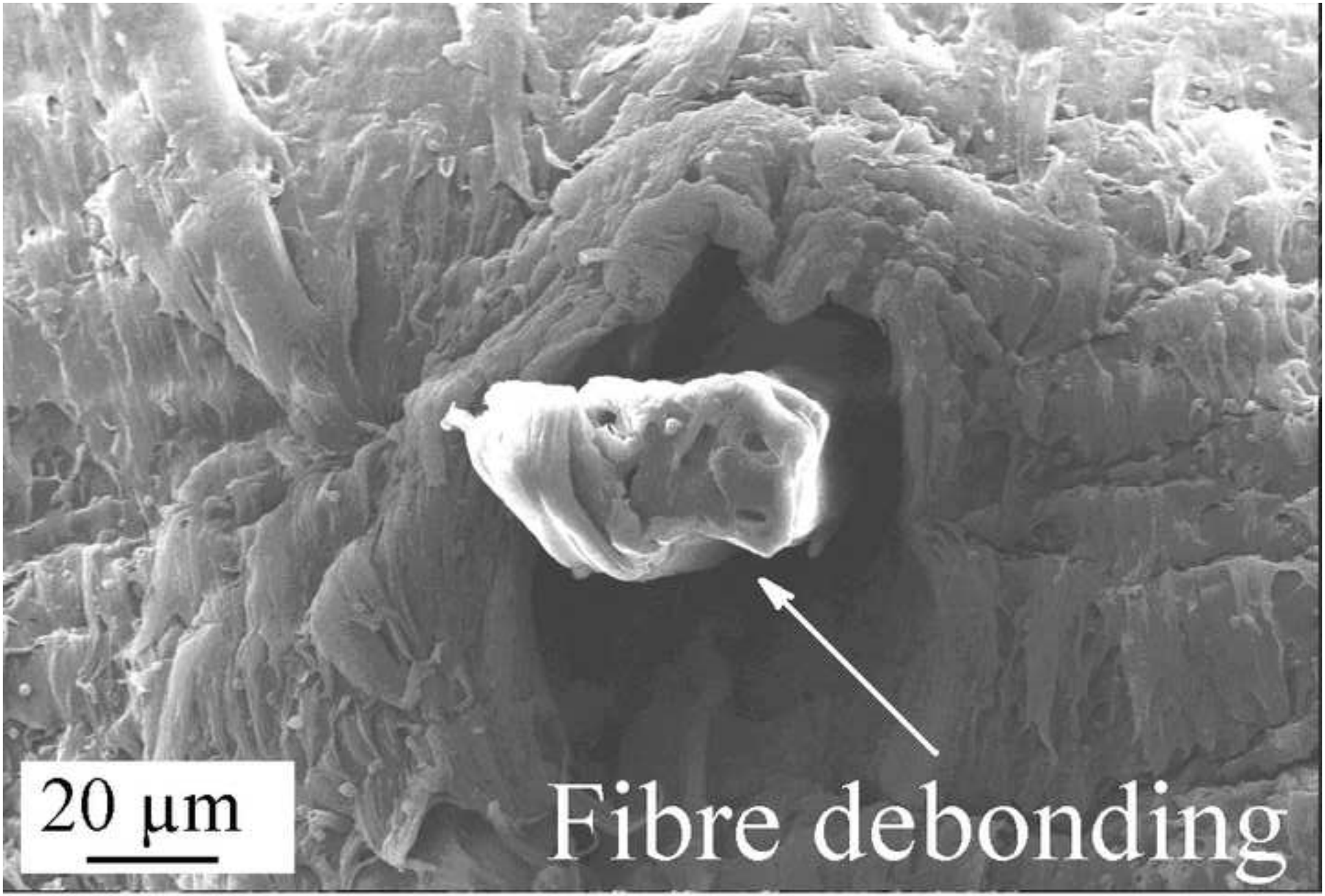

20% fibre content by mass
25% fibre content by mass
30% fibre content by mass
35% fibre content by mass
Unreinforced PP
Tensile strength (MPa)
0
20
40
60
80
Untreated kenaf fibre
1%NaOH kenaf fibre
2%NaOH kenaf fibre
3%NaOH kenaf fibre
4%NaOH kenaf fibre
5%NaOH kenaf fibre
6%NaOH kenaf fibre
7%NaOH kenaf fibre
8%NaOH kenaf fibre
Glass fibre

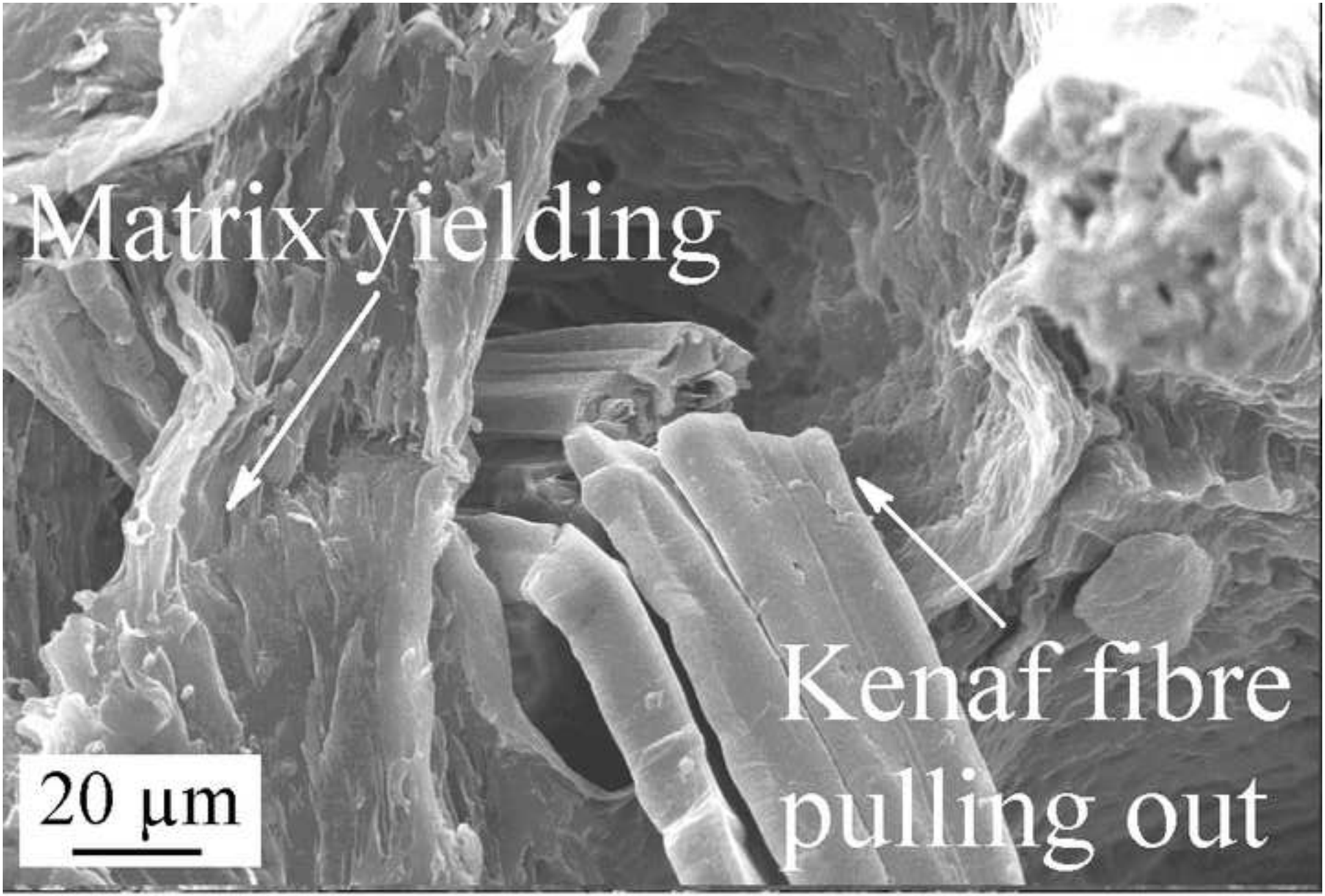
Fig. 5

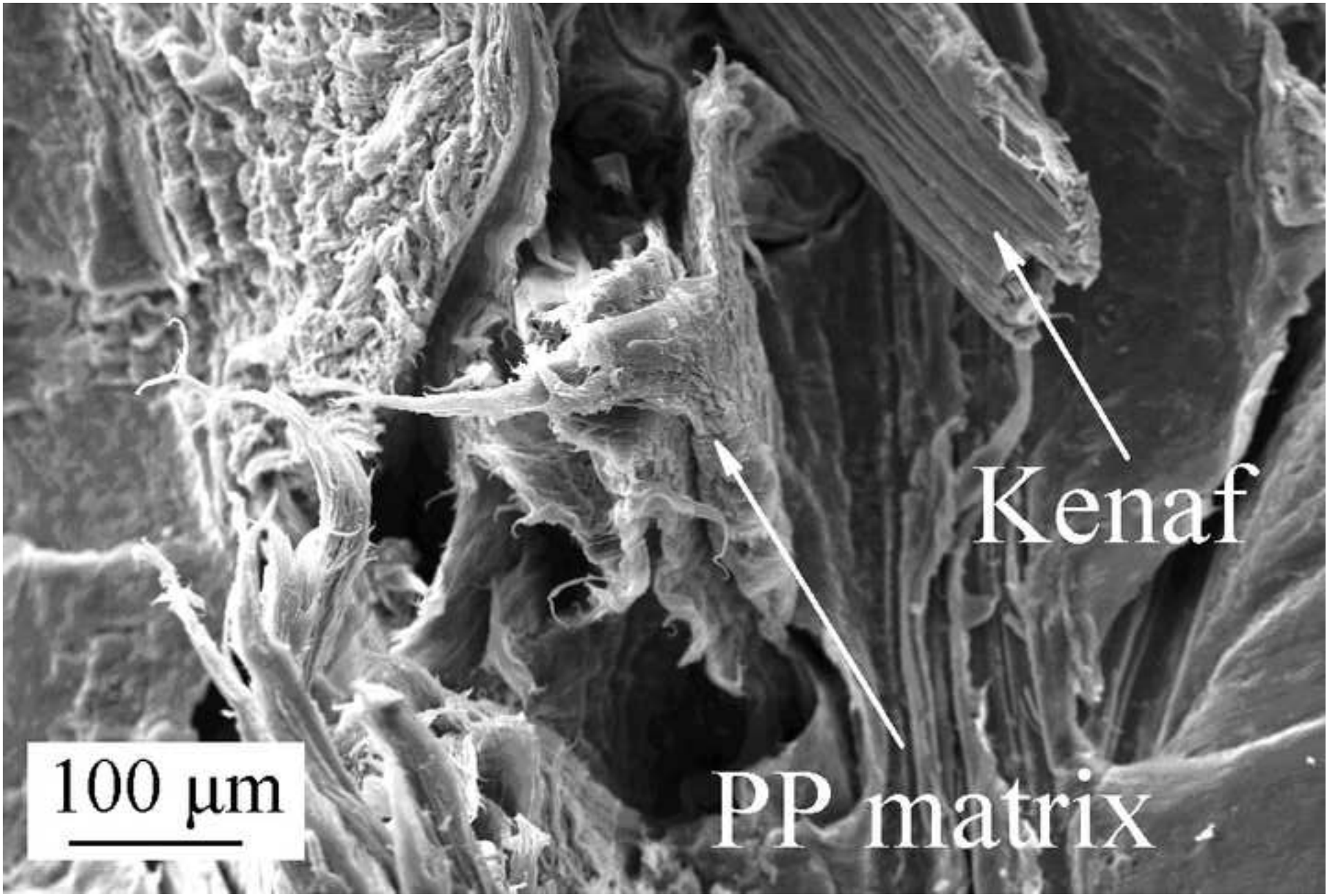

20% fibre content by mass
25% fibre content by mass
30% fibre content by mass
35% fibre content by mass
Unreinforced PP
Tensile strength (MPa)
0
20
40
60
80
Untreated kenaf fibre
1%NaOH kenaf fibre
2%NaOH kenaf fibre
3%NaOH kenaf fibre
4%NaOH kenaf fibre
5%NaOH kenaf fibre
6%NaOH kenaf fibre
7%NaOH kenaf fibre
8%NaOH kenaf fibre
Glass fibre

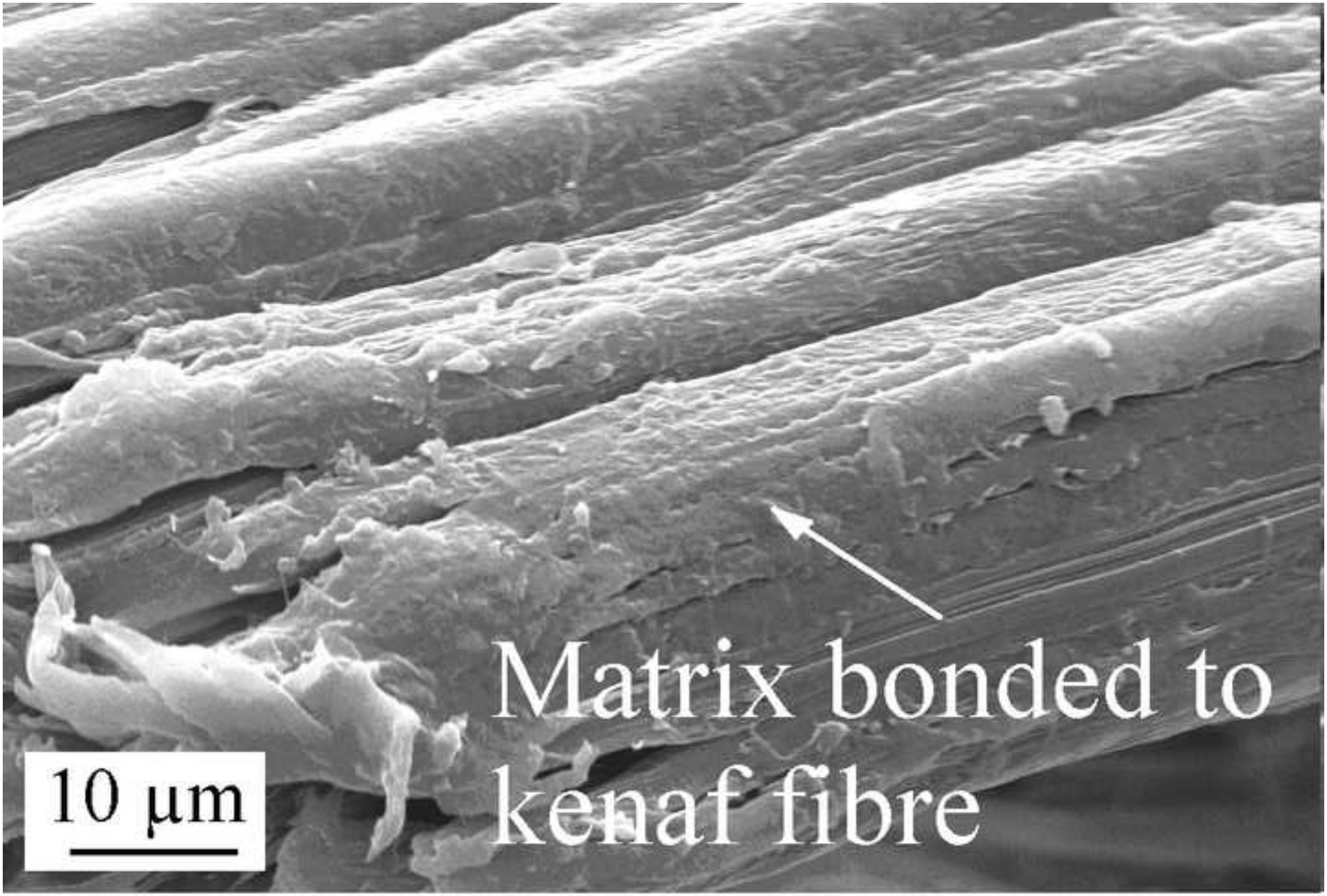

Surface deposits
100 µm

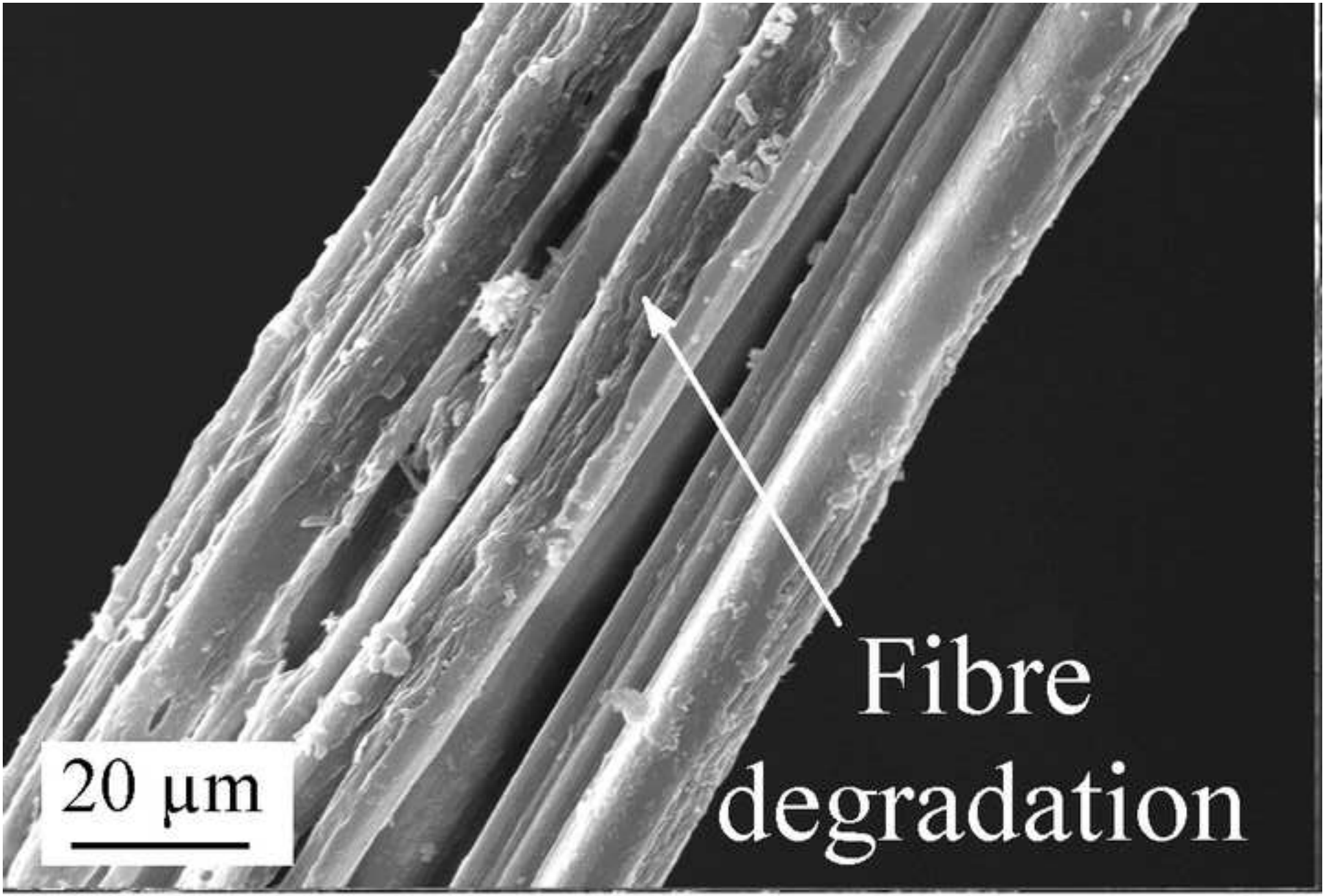

20 µm

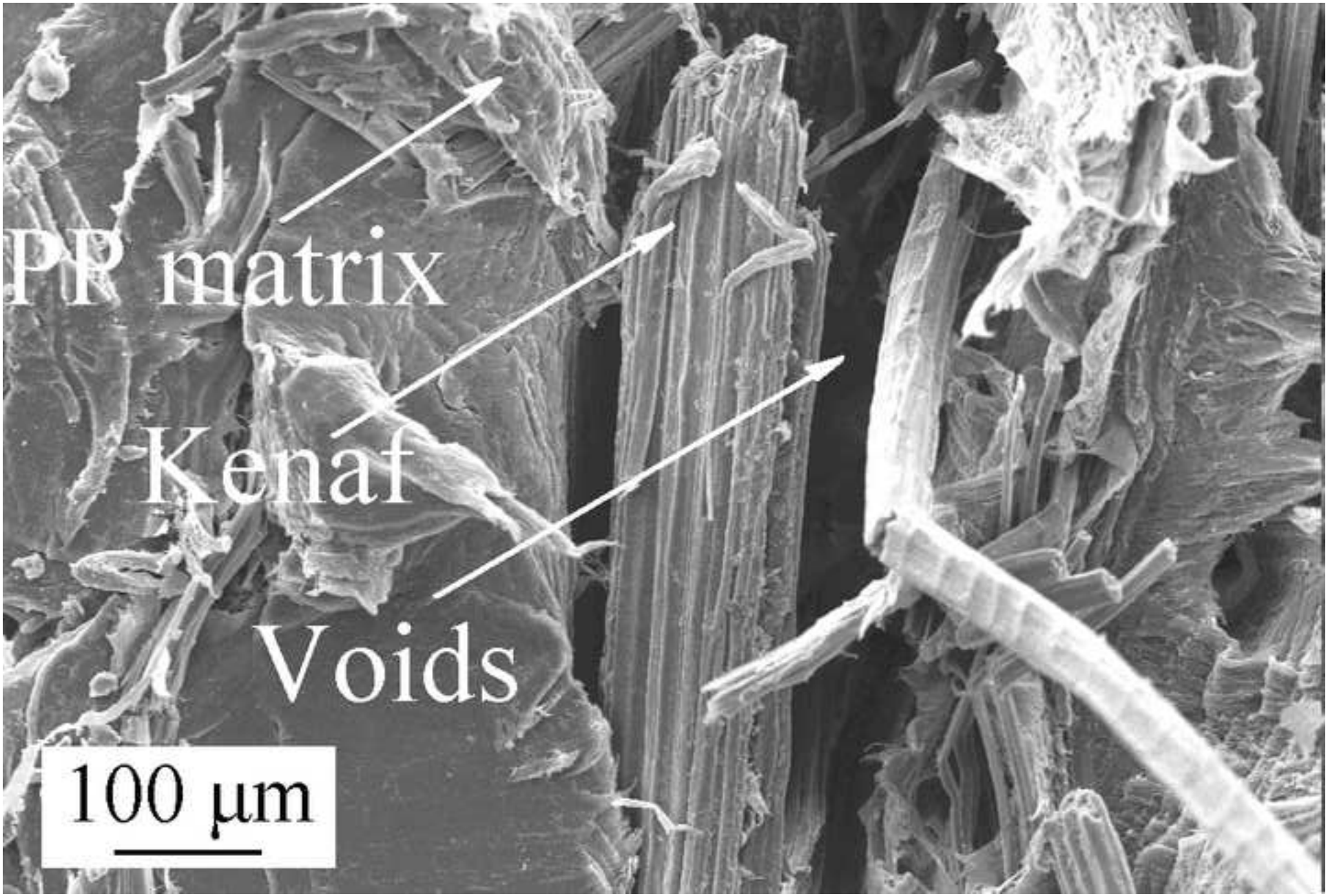

20 µm
Fibre debonding


Matrix yielding
Kenaf fibre pulling out
20 µm


Kenaf
PP matrix
100 µm


Matrix bonded to
kenaf fibre
10 µm


Fibre
degradation
20 µm


PR matrix
Kenaf
Voids
100 μm

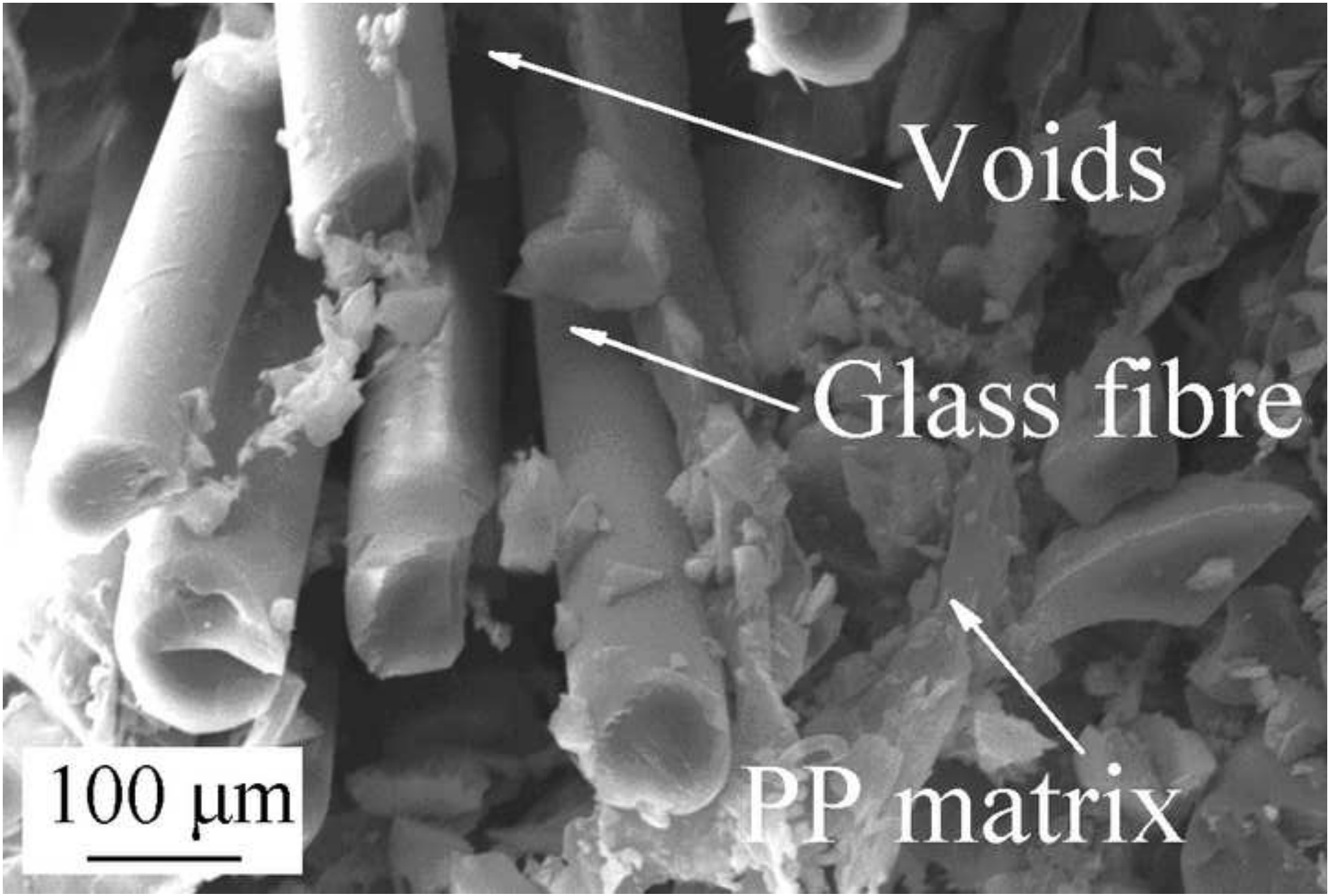

Voids
Glass fibre
PP matrix
100 µm

Fig. 15

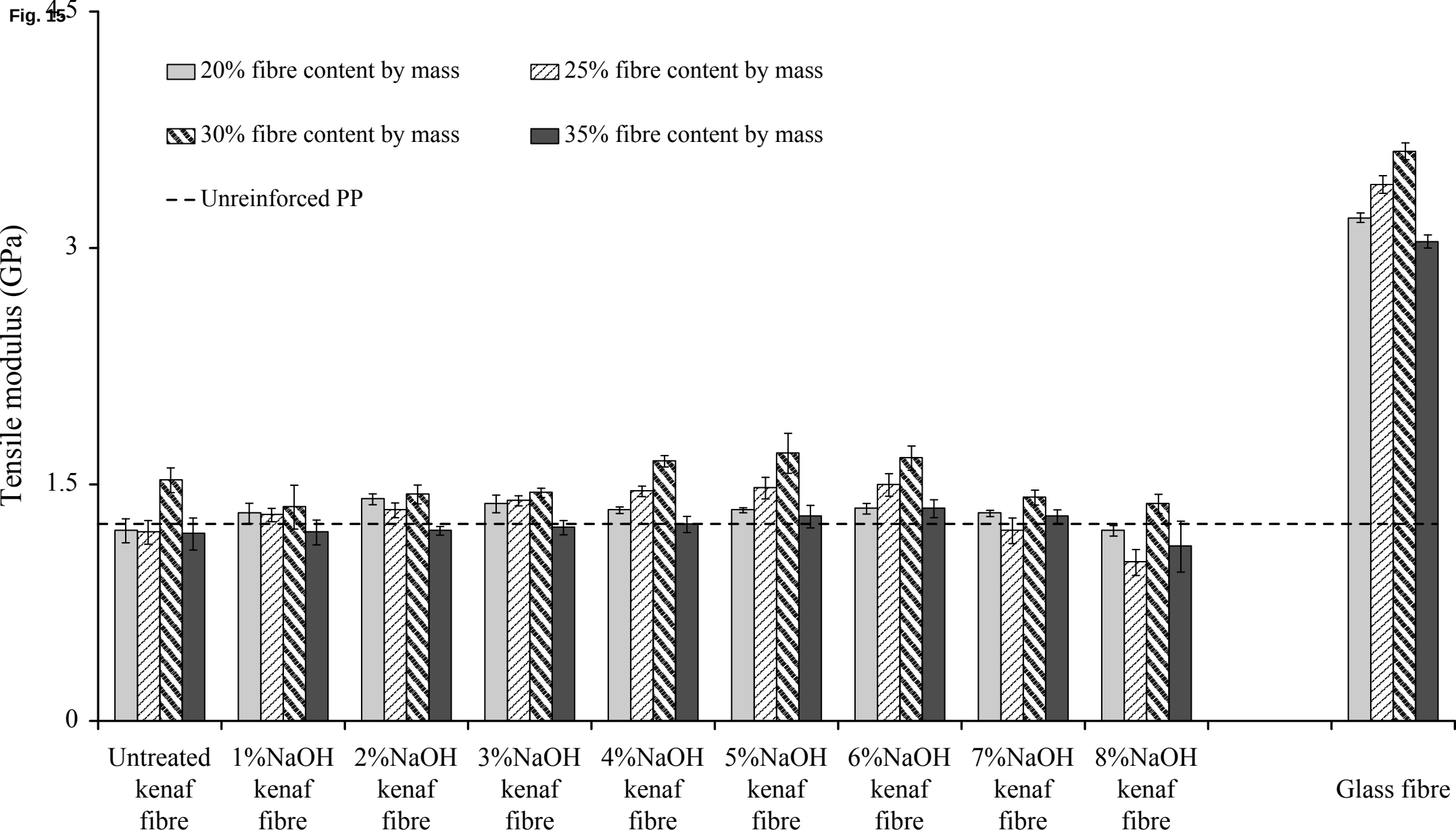

20% fibre content by mass
25% fibre content by mass
30% fibre content by mass
35% fibre content by mass
Unreinforced PP
Tensile modulus (GPa)
4.5
3
1.5
0
Untreated kenaf fibre
1%NaOH kenaf fibre
2%NaOH kenaf fibre
3%NaOH kenaf fibre
4%NaOH kenaf fibre
5%NaOH kenaf fibre
6%NaOH kenaf fibre
7%NaOH kenaf fibre
8%NaOH kenaf fibre
Glass fibre

Fig. 16

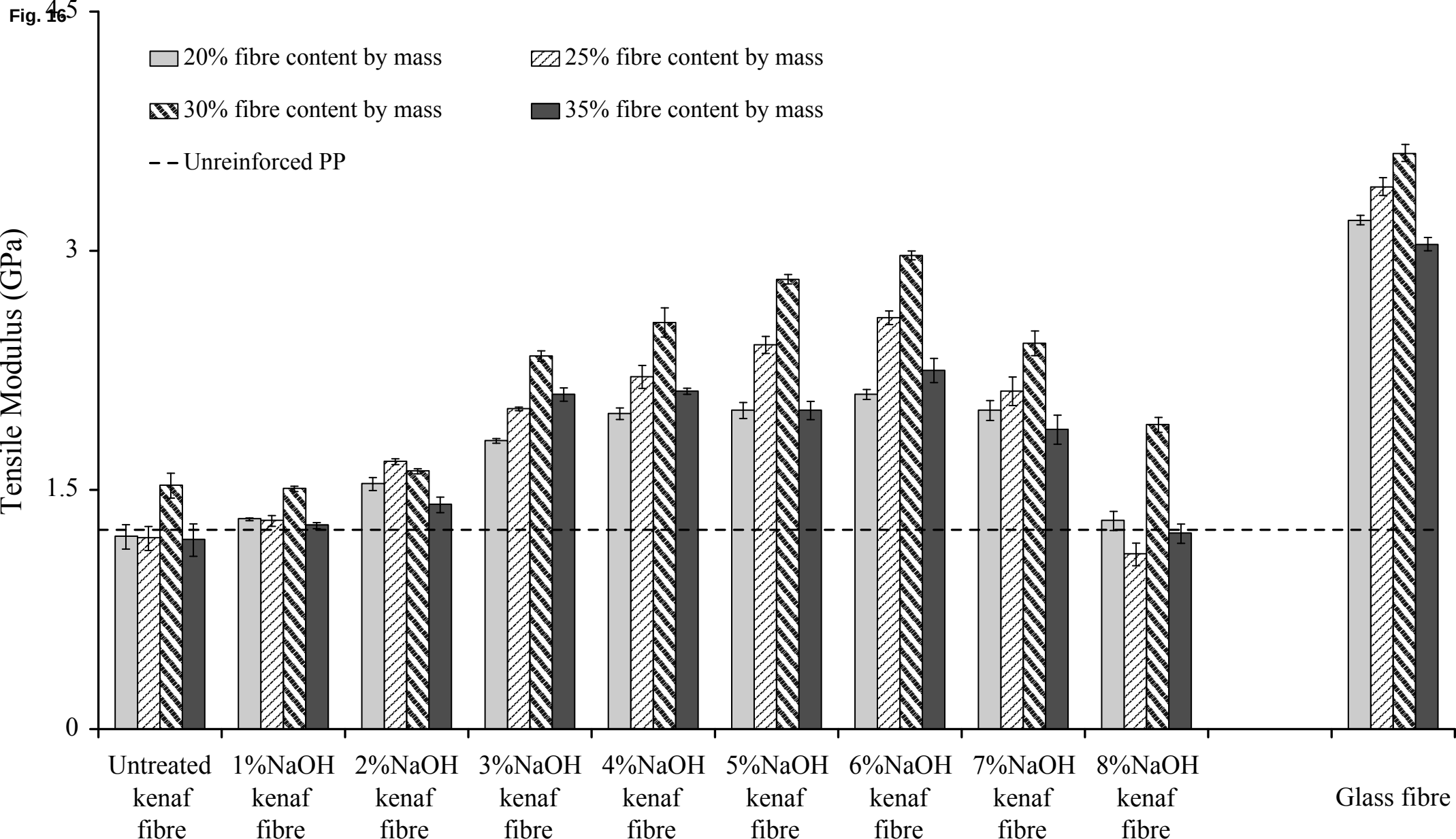

20% fibre content by mass
25% fibre content by mass
30% fibre content by mass
35% fibre content by mass
Unreinforced PP
Tensile Modulus (GPa)
4.5
3
1.5
0
Untreated kenaf fibre
1%NaOH kenaf fibre
2%NaOH kenaf fibre
3%NaOH kenaf fibre
4%NaOH kenaf fibre
5%NaOH kenaf fibre
6%NaOH kenaf fibre
7%NaOH kenaf fibre
8%NaOH kenaf fibre
Glass fibre

Fig. 17

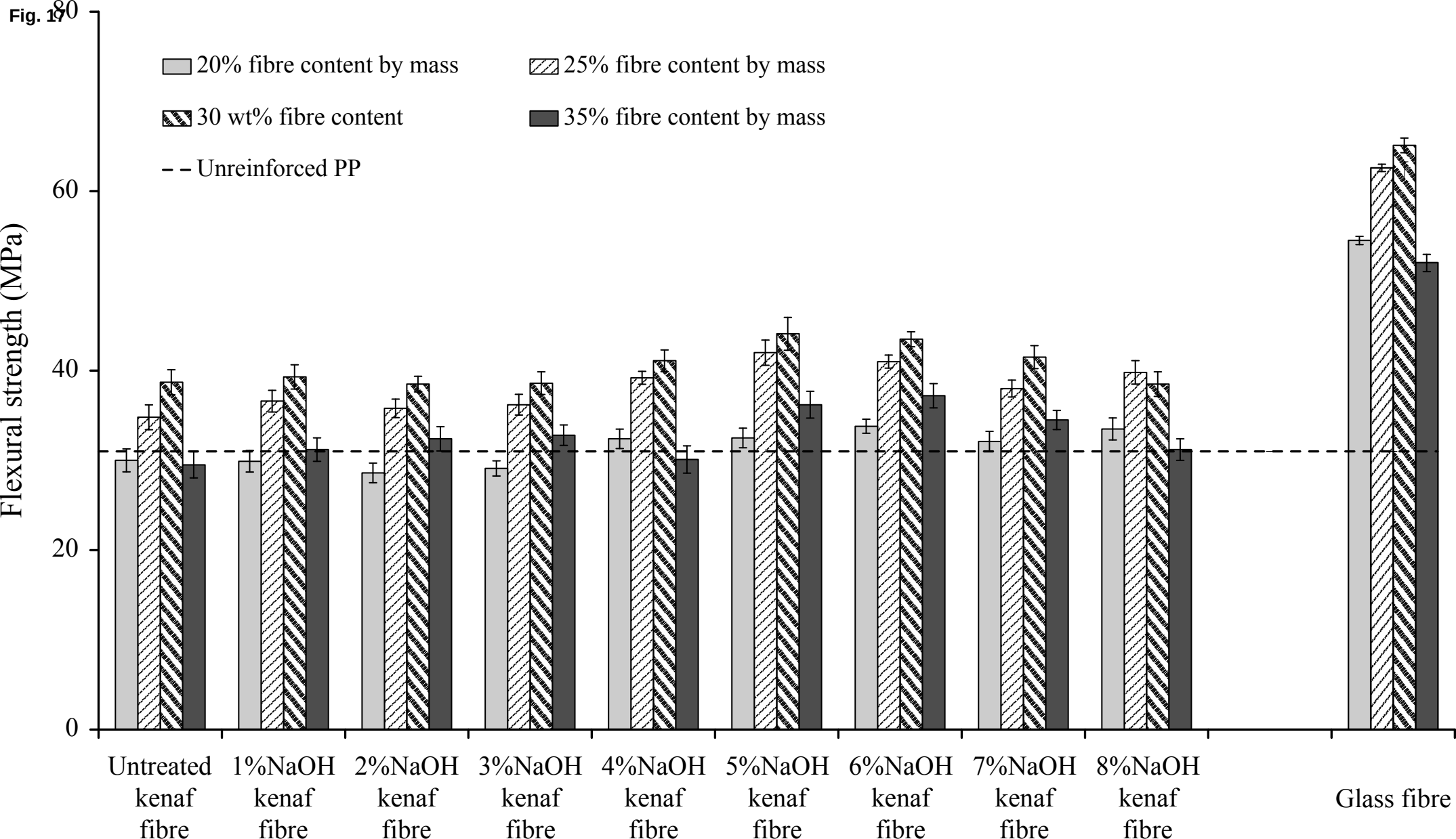

20% fibre content by mass
25% fibre content by mass
30 wt% fibre content
35% fibre content by mass
Unreinforced PP
Flexural strength (MPa)
0
20
40
60
80
Untreated kenaf fibre
1%NaOH kenaf fibre
2%NaOH kenaf fibre
3%NaOH kenaf fibre
4%NaOH kenaf fibre
5%NaOH kenaf fibre
6%NaOH kenaf fibre
7%NaOH kenaf fibre
8%NaOH kenaf fibre
Glass fibre

Fig. 18

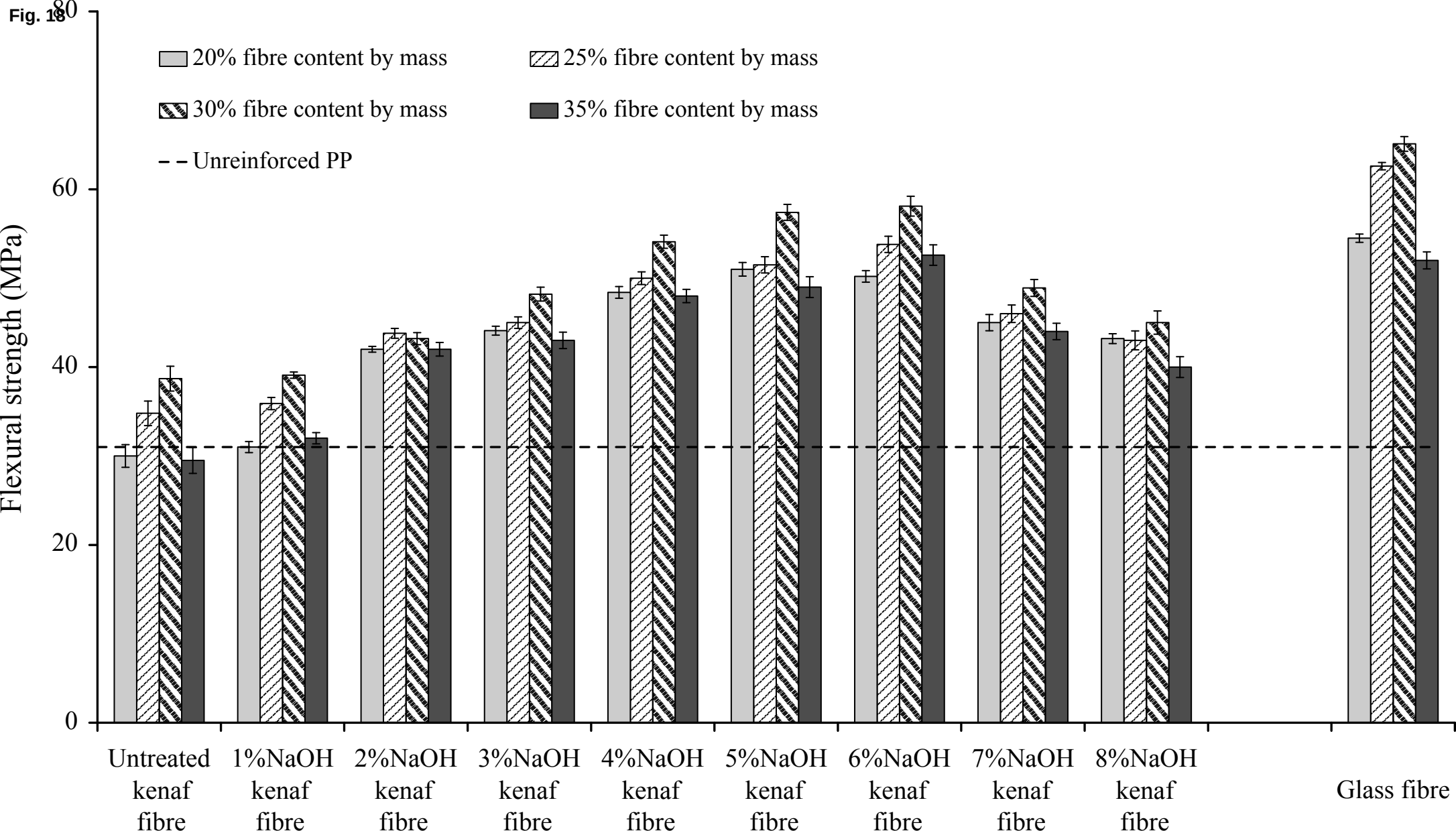

20% fibre content by mass
25% fibre content by mass
30% fibre content by mass
35% fibre content by mass
Unreinforced PP
Flexural strength (MPa)
0
20
40
60
80
Untreated kenaf fibre
1%NaOH kenaf fibre
2%NaOH kenaf fibre
3%NaOH kenaf fibre
4%NaOH kenaf fibre
5%NaOH kenaf fibre
6%NaOH kenaf fibre
7%NaOH kenaf fibre
8%NaOH kenaf fibre
Glass fibre

Fig. 19

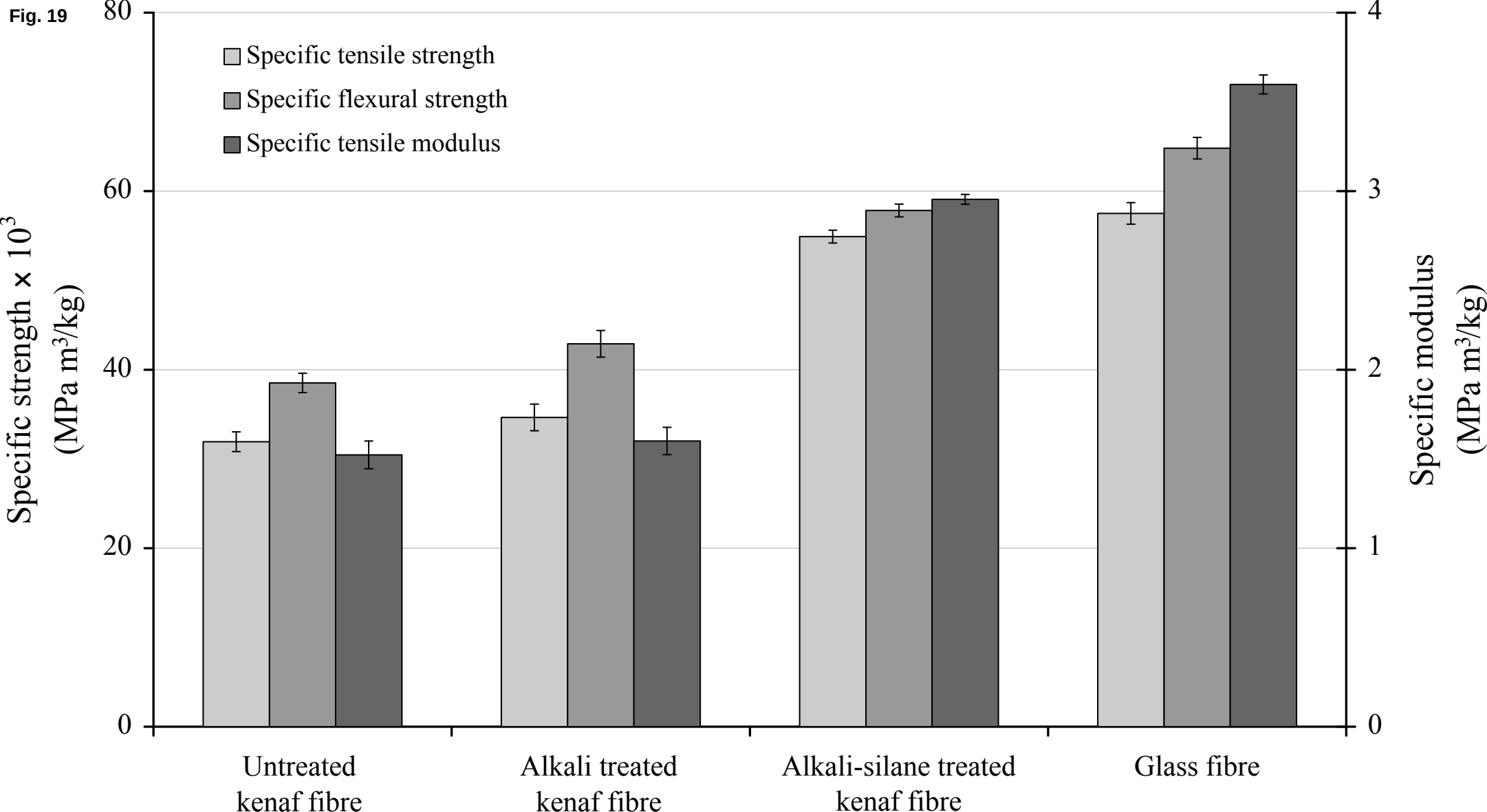

Specific tensile strength
Specific flexural strength
Specific tensile modulus
Specific strength × 10³ (MPa m³/kg)
Specific modulus (MPa m³/kg)
0
20
40
60
80
0
1
2
3
4
Untreated kenaf fibre
Alkali treated kenaf fibre
Alkali-silane treated kenaf fibre
Glass fibre

**Table 1**

Table 1 Material properties of reinforcing materials and PP matrix

| Properties | Unit | Kenaf fibre | Glass fibre | PP matrix |
|---|---|---|---|---|
| Tensile strength | MPa | 930 [21] | 1720 [22] | 30 [23] |
| Elastic modulus | MPa | 53 [21] | 72.0 [22] | 1300 [23] |
| Density | $kg/m^3$ | 1500 [24] | 2700 [22] | 910 [23] |

**Table 2**

Table 2 Manufacturing parameters

| Phase | Time (Mins) | Oven temperature (°C) | Compressive Load (bar) |
|---|---|---|---|
| 1-Compaction | 15 | 25 to 250 | 75 |
| 2-Fibre impregnation | 5 | 250 | 75 to 50 |
| 3-Compression | 15 | 250 | 50 |
| 4-Release of the compression load | 5 | 250 to 25 | 50 to 5 |
| 5-Cooling | 20 | …… | 5 |