Treatment of Firefighter's Suit against Fire to Increase Its Effectiveness

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Abstract:
Great efforts have been tried through the late years to increase the suitability and effectiveness of Firefighters suit. These efforts were done to protect the wearer from harsh environmental that may result in injury or death. This paper describes flame retardants treatment of fabrics which used in the firefighter suit to prevent and slow down fires in fabric and clarify that using the most effective flame retardants could save lives and prevent burn injuries. This paper examined the efficacy of two fire retardant substances, PF-phosphorus / nitrogen compound based and PR 20-organo phosphorus-based. The fabric samples were burned before and after machine washing with soap. Methodology was undertaken using a number of three different firefighter suit materials, with fiber content of 100% cotton, PES/cotton and 100%PES. Both treated and untreated fabrics were examined using a number of test methods; first, the flammability test, second, physical and comfort properties, finally, thermal conductivity. Fabric before and after treatment has been analyzed by using Fourier transforms infra-red spectroscopy to show the effect of the treatment on the fabrics. The resulting work of PF-phosphorus / nitrogen compound based treatment did not drained, and was found to be durable.

Keywords:
Protective clothing, Firefighter suit, flame retardants, functional properties, infra-red spectroscopy.

ملخص البحث:
هناك جهود كثيرة بذلت خلال السنوات الأخيرة لزيادة ملاءمة وفعالية ملابس رجال الاطفاء. وقد تم بذل هذه الجهود لحماية مرتديها من البيئة القاسية التي قد تؤدي إلى الإصابة بالحروق أو الوفاة. يتناول هذا البحث معالجة الأقمشة المستخدمة في ملابس رجال الاطفاء بمواد مقاومة للحريق لمنع وإبطاء الحرائق في النسيج كما توضح أن استخدام انواع من مثبطات الحريق الأكثر فعالية يمكن أن يساعد فى إنقاذ الأرواح ومنع الإصابات بالحروق. فى هذا البحث تم اختبار فعالية اثنين من المواد المقاومة للحرائق و هما:

1- PF-phosphorus / nitrogen compound based
2- PR 20-organo phosphorus-based

تم اجراء اختبار الحريق لعينات النسيج قبل وبعد غسل العينات بالصابون فى الغسالة الكهربية. و تمت المعالجة باستخدام ثلاث انواع مختلفة من أقمشة ملابس رجال الاطفاء وهى: القطن 100٪، 50%بوليستر/50%قطن، بوليستر 100%. كلا من الأقمشة المعالجة والغير معالجة تم اختبارها باستخدام عدد من طرق الاختبار، أولا: اختبار قابلية الاشتعال، ثانيا: الخصائص الفيزيائية وخواص الراحة، وأخيرا، التوصيل الحراري.
قد تم تحليل النسيج قبل وبعد المعالجة باستخدام الأشعة تحت الحمراء ولإظهار تأثير المعالجة على الأقمشة. أوضحت النتائج ان ملابس رجال الاطفاء المعالجة بمادة PF-phosphorus / nitrogen compound based اكثر مقاومة للحريق و أفضلها بعد الغسيل حيث ظلت ثابته فى الالياف و دائمة حتى بعد الغسيل.

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1. INTRODUCTION

Many hazards might happen in the Firefighters environment, toxic substances in the air, high radiant heat intensities and hot flames are all examples of these hazards and common risks in fire extinguishing work.

According to the end-use functions, we classify the personal protective textiles into thermal protection, chemical protection, flame protection, radiation protection, mechanical impact protection, electrical protection, biological protection and wearer visibility. (1)

Protective textile is a part of technical textiles which are used for their performance or functional characteristics rather than their aesthetic or decorative advantages. Classification process of personal protective clothing is very complicated as no single classification can exactly summarize all kinds of protection. Since there are so many applications that have the same class of protective clothing but different requirements in technique and protection. (2)

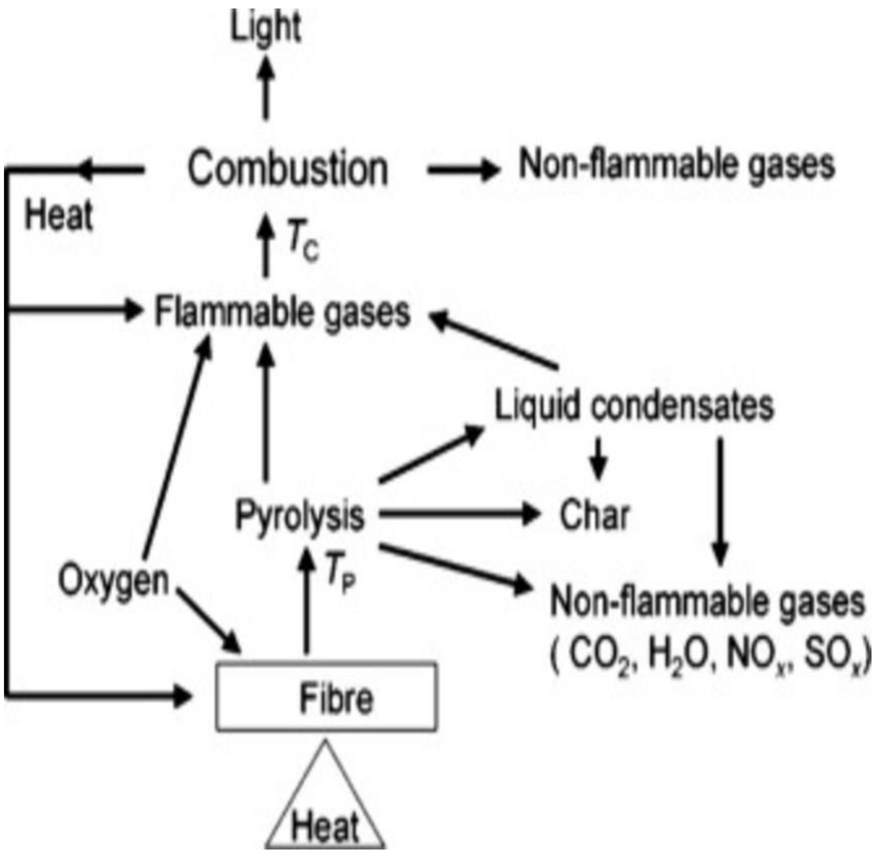


Figure (1) Combustion cycle for fibers.(2)

Flame retardancy can be conferred on textile materials by the use of ingrained flame resistant fibres, changing of fiber molecular structures by copolymerization and chemical modification methods, incorporation of flame retardant additives during the production of man-made fibers (FR-viscose) or application of flame retardant products to textile substrates by a chemical after-treatment processes.(3)

Chemical after-treatments include surface or topical treatments, coatings and functional finishes, which become a part of final fiber structure. Durability of flame retardant finishes generally depends on their adherence or bond strength to the fiber surfaces or molecular structures. Generally, the flame retardant (FR) products and their flame retardancy effects are classified as non-durable, semi-durable and durable. Durability is determined by launderability, aftercare and defined cleansing requirements, weatherability, and exposure to light, heat and atmospheric agents. (4)

Non-durable FR products are deposited on and between the fibers and no crosslinking takes place. These products adhere on fiber surfaces. Some nondurable FR finishes can resist dry-cleaning process depending on their constitution. Diammonium phosphate, borax and boric acid mixtures, ammonium sulphate, ammonium bromide and ammonium salts of amidosulphonic acid are often used as non-durable flame retardant products. Semi-durable flame retardant products may crosslink to fiber reactive groups.(3)

Flame retardancy can be maintained for 5-15 times to dry or aqueous cleaning processes, depending on their constitution. Halogenated products, such as chlorinated paraffin, polyvinyl chloride, polyvinylidene chloride, metal oxides (especially antimony trioxide in combination with halogen compounds such as hexabromocyclododecane or chlorinated paraffin) and simple phosphorus/nitrogen compounds, are often used as semi-durable FR products2 unless applied together with a resin. Durable FR products bond to the reactive groups of fiber molecules or penetrate inside the fiber. Durable FR products often consist of organo phosphorus condensates especially in the presence of cellulosic fibers. (5)

The efficiency of the FR finish on a textile fabric depends on a number of factors, e.g. fiber composition, fabric construction, FR compatibility with other finishes, end use and durability.

Successful FR finishes should combine acceptable levels of flame retardancy at an affordable cost and be applicable to textile fabrics using conventional textile finishing and coating equipment. (6)

2. Materials and Methods:

2.1 Materials

Specifications of fabrics are given in table 2. Fabrics were procured from Cairo Fire Department.

Fabric weight obtained using digital sensitive scale according to (ASTM D3776-96-2003).

Thickness obtained using thickness tester according to (ASTM D1777-96-2003).

Table1: fabric Specifications

Fabric ID	Fiber content	Weave construction	Weight g/m^2	Thickness mm
Sample 1	Cotton100%	Plain 1/1	120	0.04
Sample 2	50%PES/50%cotton	Twill 2/1	125	0.08
Sample 3	PES 100%	Plain 1/1	115	0.02

2.2. Chemicals

Table2: Chemicals Specifications

Flame retardant(**FR 1)**	PF-phosphorus / nitrogen compound based
Flame retardant**(FR 2)**	PR 20-organo phosphorus-based

2.3. Experimental Methods

2.3.1 Application of flame retardants on three different fire-fighter suit fabrics

Methodology was undertaken using a number of three different fire-fighter suit fabrics, with fiber content of 100% cotton, 50%PES/50% cotton and 100%PES. All of which were treated using two different flame retardants contains PF-phosphorus / nitrogen compound- based and PR 20-organo phosphorus-based.

Treatment has been applied on the National Research Center of Egypt, by padding fire-fighter suit fabrics. In detail, treatment was done into conditioning atmosphere of 21°C and 65% RH, first, all samples were washed using 10g/l detergent at 80°C for 15mins, to get rid of any unwanted residues. Second, samples were rinsed and left horizontally to dry into oven at 180°C for 5mins, making sure that samples have no humidity and to accept the treatment. Third,.Application to samples by pad dry cure method:, 100%cotton, 100% polyester and 50%cotton/50%polyester woven fabric were immerged in padding liquor at room temperature for 10 minutes and then passed through a two bowl laboratory padding mangle, which was running at a speed of 10 rpm with a pressure of 1.5 Kg/cm2 using 2-dip 2-nip padding sequence at 70% expression, then the sample padded again for 1 min then dried at 120^{o}C for 5 minutes and thermosetting at 150^{o}C temperature for 4 minutes.
The flammability test method normally measures char and damaged length. However, these measures do not always represent the real destroyed area of the fabric for many cases. Therefore, it was decided to use another parameter (weight loss), which will give more realistic approach to evaluate fabric destruction. It is clear that the parameters selected are interrelated or dependent on each other; high weight loss would definitely show a high area destroyed. For these reasons, flammability test and weight loss were measured for all specimens. Before and after testing the test specimens were weighed and the weight loss value was determined

2.3.2 Testing and Analysis

a) Measurement of mechanical properties:
Weight, tensile strength tester, crease recovery tester, elongation tester.

b) Measurement of thermo comfort properties:
Air permeability test, water vapor transfer rate test, thermal conductivity test, wettability test.

c) Measurement of functional properties:
In this study, flammability test was replicated four times for each sample and the total of samples was tested to evaluate the effects of finishes.
A standard flame was applied at the bottom edge of the fabric for 30 s under controlled conditions. All Flammability tests were conducted under ambient temperature and relative humidity in the laboratory. This flammability test method normally measures char and damaged length.

d) Infra-red (IR): The chemical transformations have been analyzed using Infra-Red (IR).
The changes in functional properties as Flame retardancy are tested before and after washing and IR analysis which used to study the surface morphology and structural compositions.

3. Results and Discussion:

In this part it has been used a two different flame retardant treatment chemicals, PF-phosphorus / nitrogen compound- based and PR 20-organo phosphorus-based to be compared by the three different materials woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester before and after washing.

1- Weight

The following table3 illustrate the weight of the fabrics before and after burning

Table3: Tested fabrics weight before and after burning

sample treatment type	Weight (gm/m2)	
	before burning	**after burning**
100% cotton untreated	120	56
100% cotton (FR 1)	123	121
100% cotton (FR 2)	123	98
100% polyester untreated	115	40
100% polyester (FR 1)	119	118
100% polyester (FR 2)	120	92
PES/cotton 50%/50% untreated	125	48
PES/cotton50%/50% (FR 1)	128	127
PES/cotton 50%/50% (FR 2)	129	90

The flammability test does not always represent the real destroyed area of the fabric Therefore, it was decided to use another parameter (weight loss), which will give more realistic approach to evaluate fabric destruction. High weight loss would definitely show a high area destroyed. Before and after testing the test specimens were weighed and the weight loss value was determined using the following relationship:

$$\text{Weight loss} = \frac{\text{Initial weight of specimen} - \text{Last weight of specimen}}{\text{Initial weight of specimen}}$$

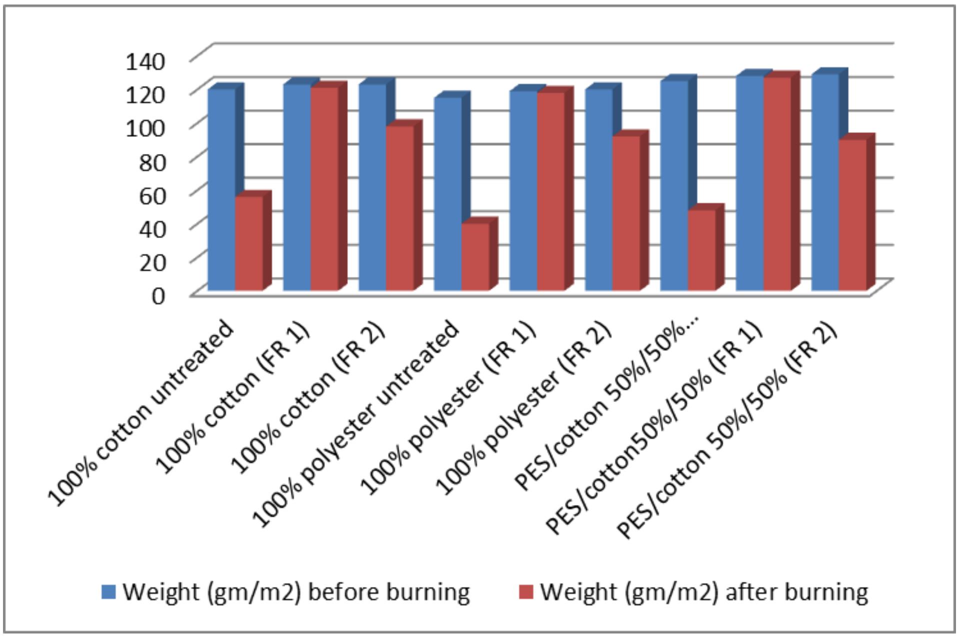


Figure (2) the relation between FR type and weight loss behavior of the treated fabrics

With respect to the effect of (FR1) and (FR2) Treatment finishing agents on vertical strip test behavior, results from the analysis show that weight loss values of the fabrics are highly affected from FR types (Table 3). When using (FR1), there is a decrease in the weight loss of the fabrics. When the FR type changes to a (FR2), there is a decrease in the weight loss of the fabrics.

Figure 2 shows the relation between FR type and weight loss behavior of the fabrics. This decrease in the weight loss values can probably be attributed to the enhanced active agent content of the flame retardant products generated by the durable FR product. The increase in active agent content results in an increase in degree of flame retardance consuming more combustion energy and producing less flammable volatiles and hence reduced weight loss.

2- The effect of Flame Retardant treatment on fabrics tensile strength

Table4: Tested fabrics tensile strength after flame retardant treatment

sample treatment type	tensile strength kg/cm2	
	before washing	after washing
100% cotton untreated	108.5	107.5
100% cotton (FR 1)	102	85.7
100% cotton (FR 2)	106	98.5
100% polyester untreated	221.4	221.4
100% polyester (FR 1)	240	233.8
100% polyester (FR 2)	256.7	251
PES/cotton 50%/50% untreated	212.5	212.5
PES/cotton50%/50% (FR 1)	234	237.6
PES/cotton 50%/50% (FR 2)	242	228

Sample tensile strength is a measurement of the force required to pull the material before breaking. Table 4 shows tensile strength of (untreated, (FR 1) and (FR 2) treatment) on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

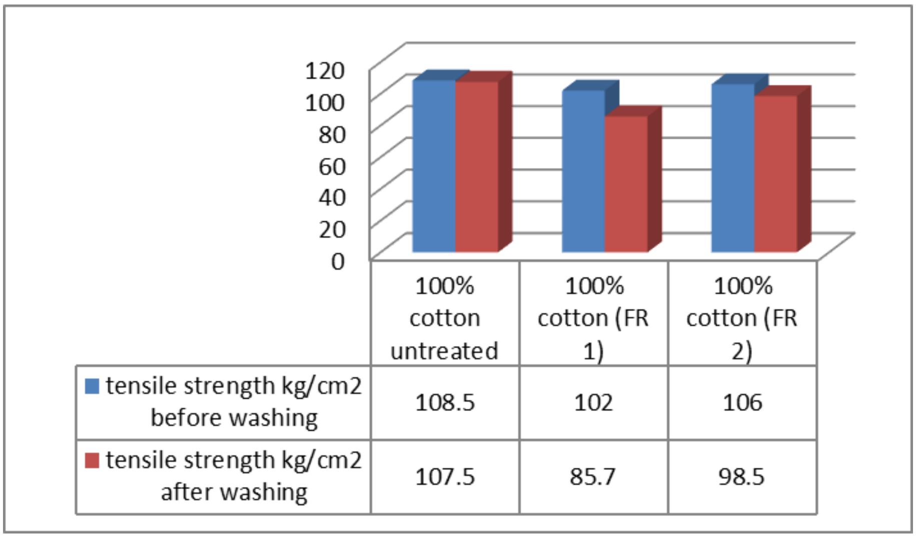


Figure (3).The difference between (FR1) and (FR2) Treatment on tensile strength for 100% cotton

Table 4 and fig.(3) Shows that flame retardant treatment affect the fabric tensile strength. Before washing, by comparing the treated sample with the 100% Cotton untreated that has 108.5 kg/cm2 found that the sample 100% Cotton (FR1) treatment decreased tensile strength to be 102kg/cm2 , and the sample (FR2) treatment decreased to be 106 kg/cm2. After washing, by comparing the treated sample with the 100% Cotton untreated that has 107.9 kg/cm2 found that the sample 100% Cotton (FR1) treatment decreased tensile strength to be 85.7 kg/cm2, and the sample (FR2) treatment decreased to be 98.5 kg/cm2.

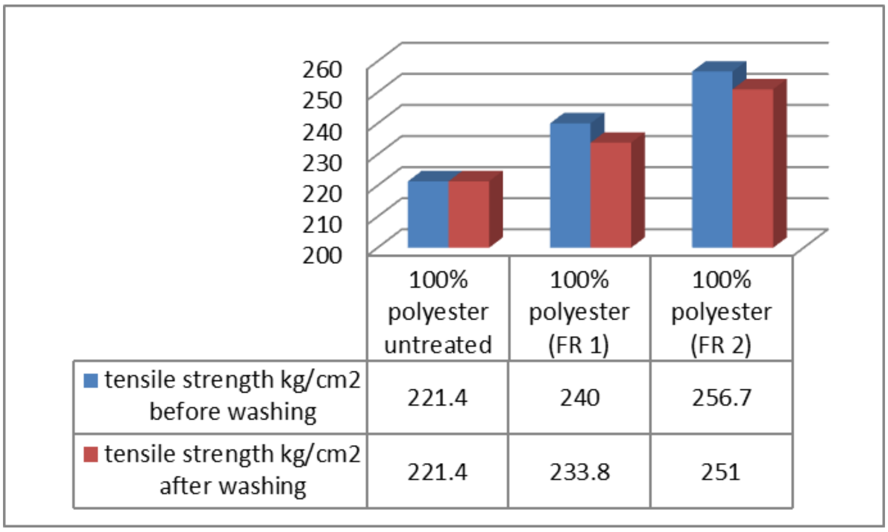


Figure (4).The difference between (FR1) and (FR2) Treatment on tensile strength for 100% polyester

Figure 4 Shows that the tensile strength increase before washing, compared to 100% polyester untreated sample 221.4 kg/cm2 to be 240 kg/cm2 for 100% polyester (FR1) treatment and for the sample 100% Polyester with (FR2) treatment increased to be 256.7 kg/cm2. After washing, compared to 100% polyester untreated sample 221.4 kg/cm2 to increase the tensile strength to be 233.8 kg/cm2 for 100% polyester (FR1) treatment sample and for the sample 100% Polyester with (FR2) treatment increased to be 251 kg/cm2

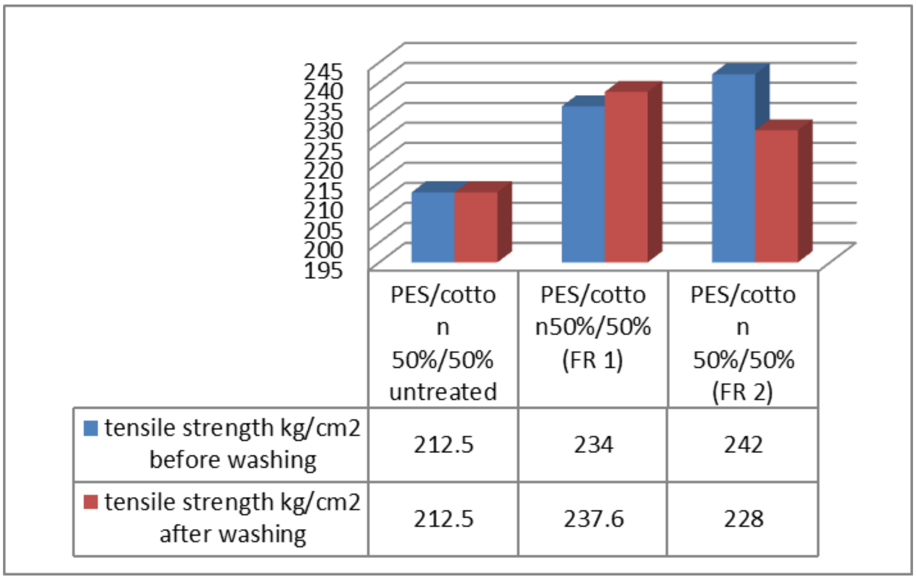


Figure (5).The difference between (FR1) and (FR2) Treatment on tensile strength for 50%PES/50% cotton

The woven fabrics blended 50% Polyester, 50% Cotton sample found that measuring the tensile strength for the untreated sample 212.5 kg/cm2 and the flame retardant treatment influenced the tensile strength, Figure 5 Shows that the tensile strength increase before washing to be 234 kg/cm2 for (FR1) treatment sample and increase the tensile strength to be

242 kg/cm2 for the blended (FR2) treatment sample. After washing cause to the increase tensile strength to be 237.6 kg/cm2 for the (FR1) treatment sample. This would be explained by the flame retardant particles which coated the fibers and penetrates them, thus make fabric more durable and long lasting. Show the best tensile strength. But On the contrary the tensile strength decrease to be 228 kg/cm2 for the (FR2) treatment sample sprayed.

3- The effect of Flame Retardant treatment on fabrics Crease Recovery Angle

Table5: Tested fabrics crease recovery angle after flame retardant treatment

sample treatment type	Crease Recovery Angle (W+F)^{O}	
	before washing	after washing
100% cotton untreated	115	110
100% cotton (FR 1)	130	130
100% cotton (FR 2)	125	112
100% polyester untreated	125	120
100% polyester (FR 1)	135	135
100% polyester (FR 2)	130	95
PES/cotton 50%/50% untreated	129	125
PES/cotton50%/50% (FR 1)	132	132
PES/cotton 50%/50% (FR 2)	130	109

Sample crease recovery angle, the ability of a creased or wrinkled fabric to recover its original shape over time by measurement of the recovery angle. Table 5 shows crease recovery angle (untreated, (FR 1) and (FR 2) treatment) on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

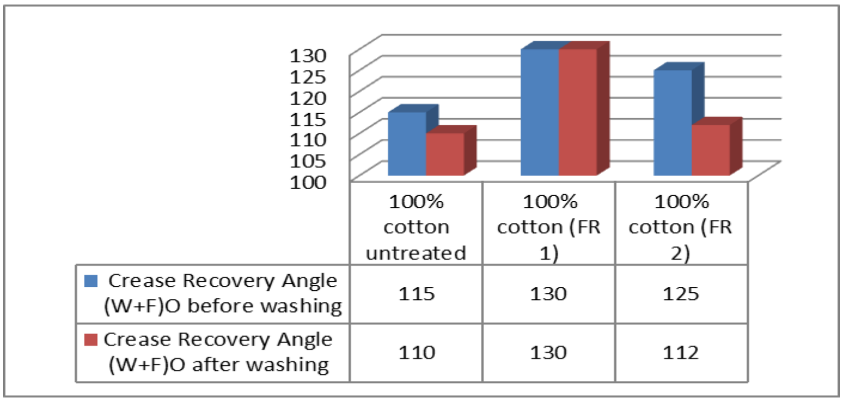


Figure (6).The difference between (FR1) and (FR2) Treatment on Crease Recovery Angle for 100% cotton

Table 6 and fig (5) Shows that flame retardant treatment affect the crease recovery angle of the fabrics. Before washing, by comparing the 100% Cotton untreated that has 115 with the sample 100% Cotton (FR1) treatment found increase in crease recovery angle to be 130, and the sample (FR2) treatment increased to be 125. After washing, by comparing the 100% Cotton untreated that has 110 found that the sample 100% Cotton (FR1) treatment increased crease recovery angle to be 130, and the sample (FR2) treatment increased to be 112.

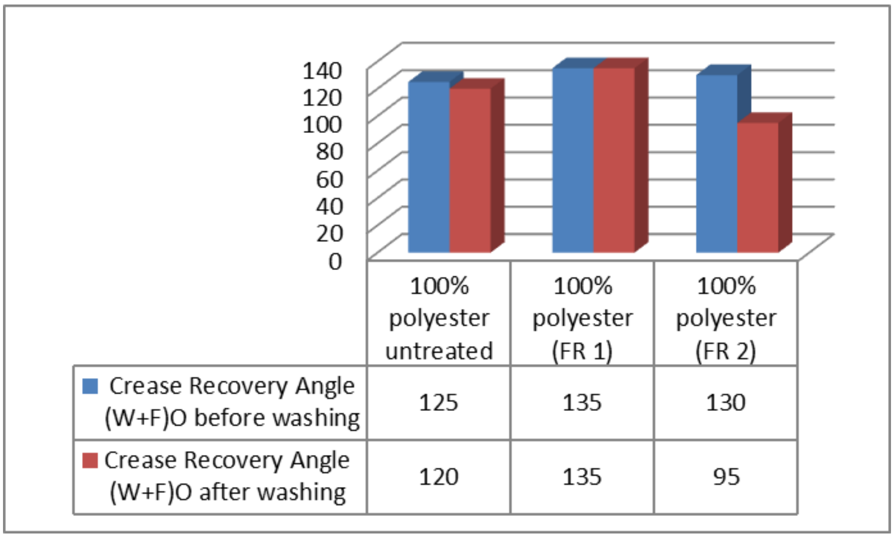


Figure (7).The difference between (FR1) and (FR2) Treatment on Crease Recovery Angle for 100% polyester

For a sample 100% Polyester (as shown in figure 7) Before washing, found an increase in the crease recovery angle compared to 100% polyester untreated sample 125 to increase the crease recovery angle to be 135 for 100% polyester (FR1) treatment sample and for the sample 100% Polyester with (FR2) treatment decreased to be 130. After washing, found a decrease in the crease recovery angle compared to 100% polyester untreated sample 120 to increase the crease recovery angle to be 135 for 100% polyester (FR1) treatment sample and for the sample 100% Polyester with (FR2) treatment decreased to be 95.

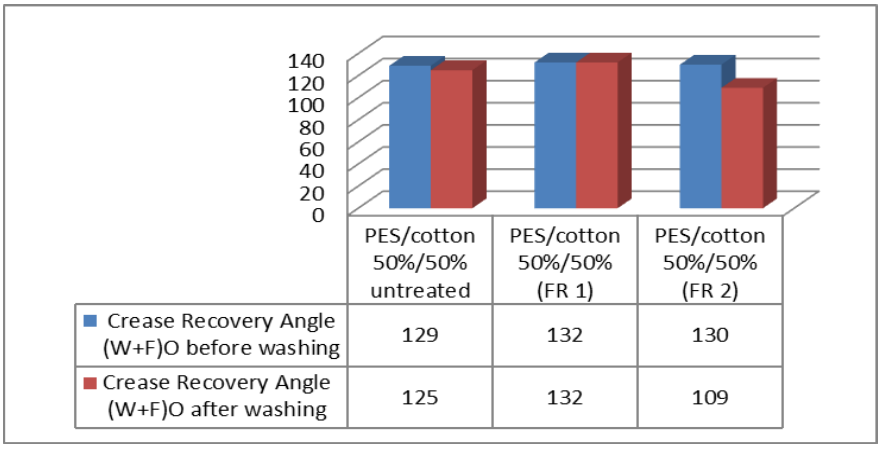


Figure (8).The difference between (FR1) and (FR2) Treatment on Crease Recovery Angle for 50%PES/50% cotton

The woven fabrics 50%PES/50% cotton sample found that measuring of crease recovery angle for the untreated sample 129 and the treatment with flame retardant influenced the crease recovery angle. Before washing, treatment caused to increasing crease recovery angle to be 132 for the (FR1) treatment sample 50%PES/50% cotton and decrease the crease recovery angle to be 130 for the blended (FR2) treatment. After washing, treatment caused to increase crease recovery angle to be 132 for the (FR1) treatment sample blended and decrease crease recovery angle to be 109 for (FR2) treatment (as shown in figure 8).This would imply that flame retardant finished woven fabrics by PF-phosphorus / nitrogen compound based for the 50%PES/50% cotton woven fabric shows the best crease recovery angle which is more durable after washing.

4- The effect of Flame Retardant treatment on fabrics Elongation at break

Table6: Tested fabrics elongation at break after flame retardant treatment

sample treatment type	Elongation at break %	
	before washing	after washing
100% cotton untreated	12.82	12.82
100% cotton (FR 1)	15.28	14
100% cotton (FR 2)	15.45	14.17
100% polyester untreated	15.8	15.8
100% polyester (FR 1)	16.5	15.89
100% polyester (FR 2)	18.5	18.38
PES/cotton 50%/50% untreated	17.83	17.83
PES/cotton50%/50% (FR 1)	18.6	18.43
PES/cotton 50%/50% (FR 2)	19.74	18.86

Elongation at break expresses the capability of a material to resist changes of shape without crack formation. Table 5 shows elongation at break of (untreated, (FR 1) and (FR 2) treatment) on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

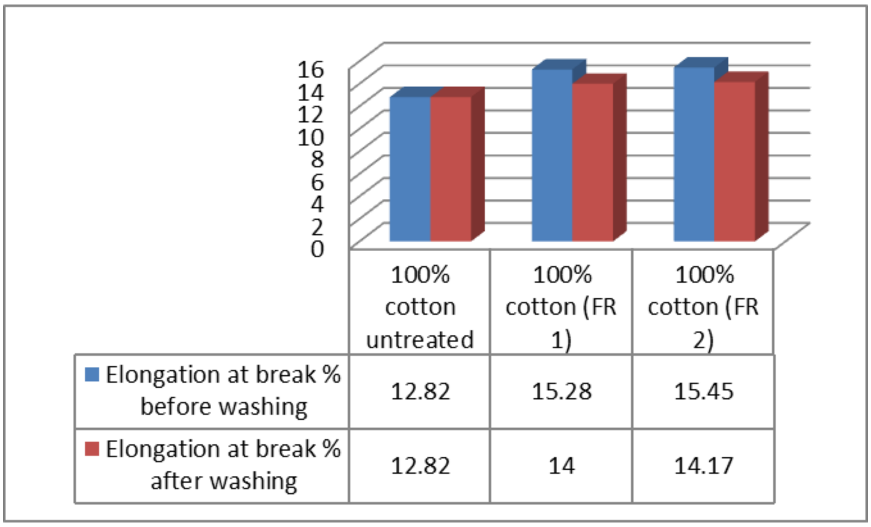
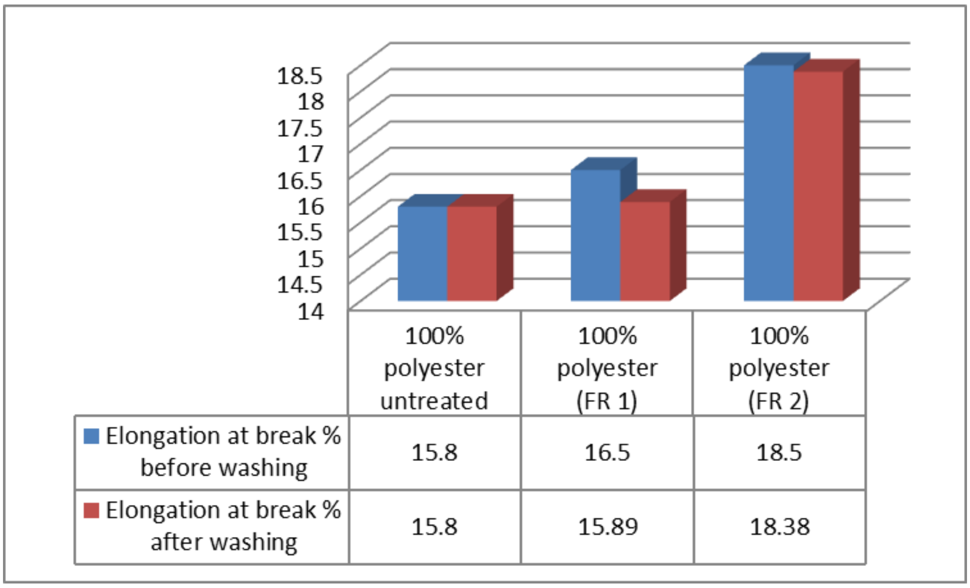


Figure (9).The difference between (FR1) and (FR2) Treatment on Elongation at break for 100% cotton

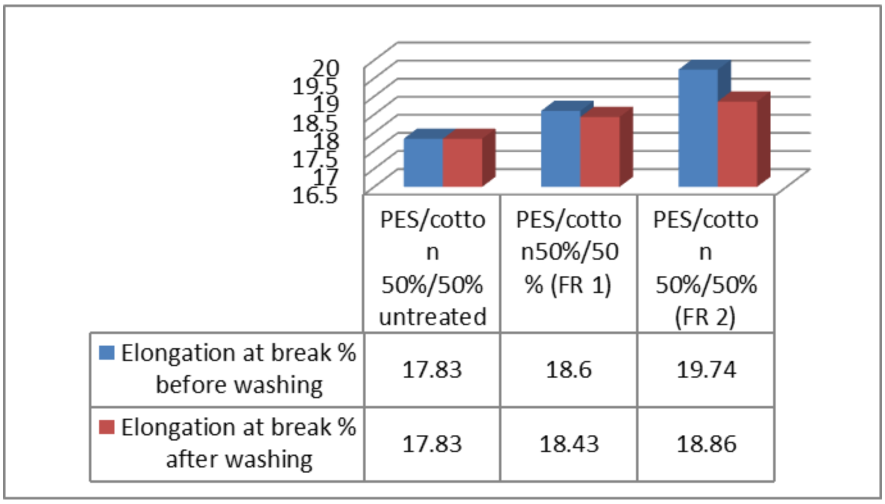
Elongation at break for flame retardant treatment woven fabric samples shows that, Before washing and by comparing the treated sample with the 100% Cotton untreated that has 12.82% found that the sample 100% Cotton (FR1) treatment increased elongation at break to be 15.28 %, and the sample (FR2) treatment increased to be 15.45% . After washing and by comparing the treated sample with the 100% Cotton untreated that has 12.82% found that the sample 100% Cotton (FR1) treatment increased elongation at break to be 14 %, and the sample (FR2) treatment increased to be 14.17% (as shown in figure 9).



	100% polyester untreated	100% polyester (FR 1)	100% polyester (FR 2)
Elongation at break % before washing	15.8	16.5	18.5
Elongation at break % after washing	15.8	15.89	18.38

Figure (10).The difference between (FR1) and (FR2) Treatment on Elongation at break for 100% polyester

for a sample 100% Polyester (as shown in figure 10) found increase in the elongation at break compared to 100% polyester untreated sample 15.8 % , before washing, it increased to be 16.5 % for 100% polyester (FR1) treatment sample and for the sample 100% Polyester with (FR2) treatment increased to be18.5 %. After washing, it increased the elongation at break to be 15.89% for 100% polyester (FR1) treatment sample and for the sample 100% Polyester with (FR2) treatment increased to be18.38 %.



	PES/cotton 50%/50% untreated	PES/cotton50%/50% (FR 1)	PES/cotton 50%/50% (FR 2)
Elongation at break % before washing	17.83	18.6	19.74
Elongation at break % after washing	17.83	18.43	18.86

Figure (11).The difference between (FR1) and (FR2) Treatment on Elongation at break for 50%PES/50% cotton

As shown in figure 11, the blended 50%PES/50% cotton sample found that measuring of elongation at break for the untreated sample 17.83% and the treatment with flame retardant influenced the elongation at break. Before washing, elongation at break increased to be 18.6 % for the (FR1) treatment sample and increase in elongation at break to be 19.74 % for the 50%PES/50% cotton (FR2) treatment. After washing, elongation at break increased to be 18.43 % for the (FR1) treatment sample and increased the elongation at break to be 18.86 % for the 50%PES/50% cotton sample (FR2) treatment.

5- The effect of Flame Retardant treatment on fabrics water air permeability

Table7: Tested fabrics water air permeability after flame retardant treatment

sample treatment type	Air permeability cm3/cm2/sec	
	Before washing	after washing
100% cotton untreated	5.643	5.643
100% cotton (FR 1)	5.682	5.975
100% cotton (FR 2)	5.305	5.622
100% polyester untreated	6.83	6.83
100% polyester (FR 1)	6.176	6.7
100% polyester (FR 2)	4.756	5.53
PES/cotton 50%/50% untreated	9.4	9.4
PES/cotton50%/50% (FR 1)	9.4	9.9
PES/cotton 50%/50% (FR 2)	9	9.5

The fabric air permeability is a measure of how well it allows the passage of air through it. Table 7 shows air permeability of (untreated, (FR 1) and (FR 2) treatment) on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

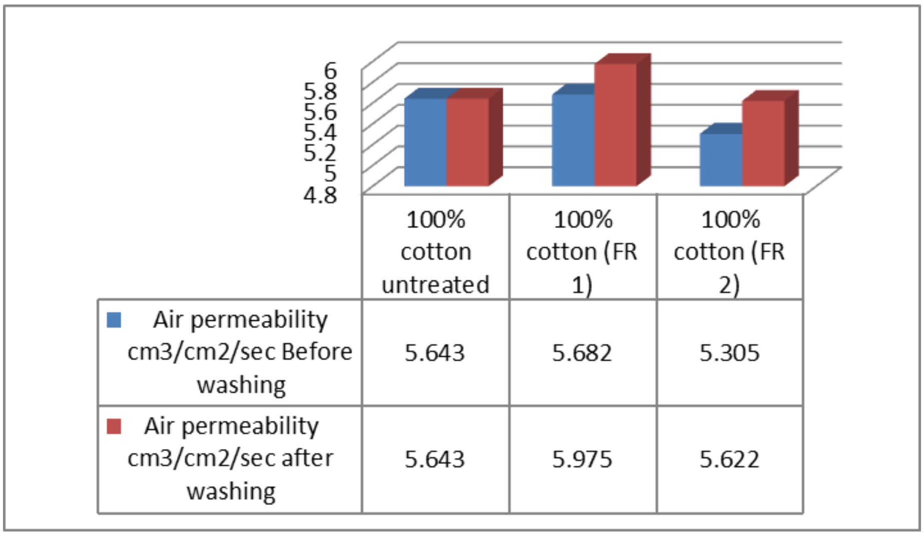


Figure (12).The difference between (FR1) and (FR2) Treatment on water air permeability for 100% cotton

Table 7 and fig (12) Shows that flame retardant treatment affect the air permeability. Before washing, the untreated 100% cotton fabric sample has 5.643cm3/cm2 /sec and the 100% cotton (FR1) treatment sample increased to be 5.682cm3/cm2 /sec air permeability, and the (FR2) treatment sample decreased to 5.305 cm3/cm2 /sec. After washing, the untreated sample has 5.643cm3/cm2 /sec and the 100% cotton (FR1) treatment sample increased to be 5.975 cm3/cm2/sec air permeability, and the (FR2) treatment sample decreased to 5.622 cm3/cm2 /sec.

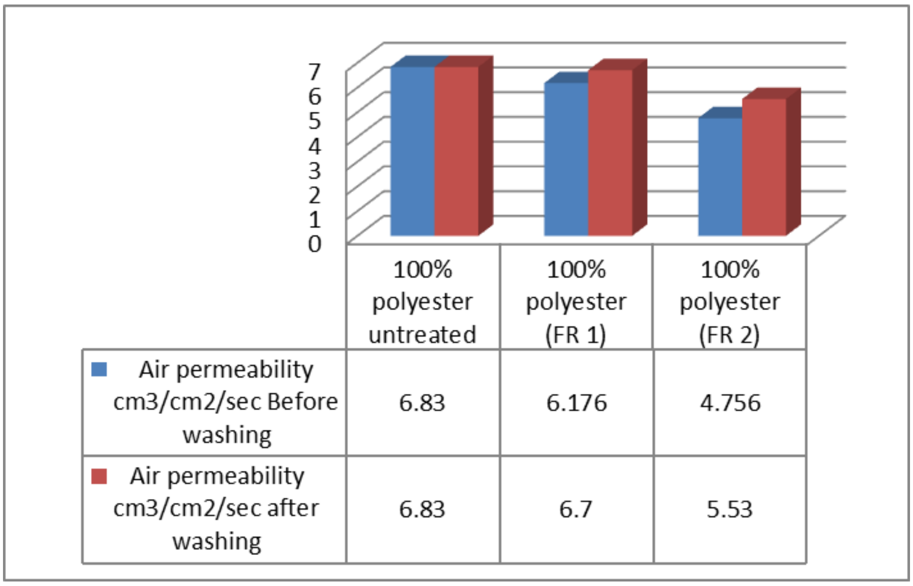


Figure (13).The difference between (FR1) and (FR2) Treatment on water air permeability for 100% polyester

As shown in figure 13, for 100% Polyester sample, before washing, found an increase in the percentage of air permeability compared to untreated sample 6.83 cm3/cm2 /sec to become 6.176 cm3/cm2 /sec for (FR1) treatment sample and for the (FR2) treatment sample decreased to become 4.756 cm3/cm2 /sec. After washing, found a decrease in the percentage of air permeability compared to untreated sample 6.83cm3/cm2 /sec to become 6.7 cm3/cm2 /sec for (FR1) treatment sample and for (FR2) treatment sample decreased to become 5.53 cm3/cm2 /sec.

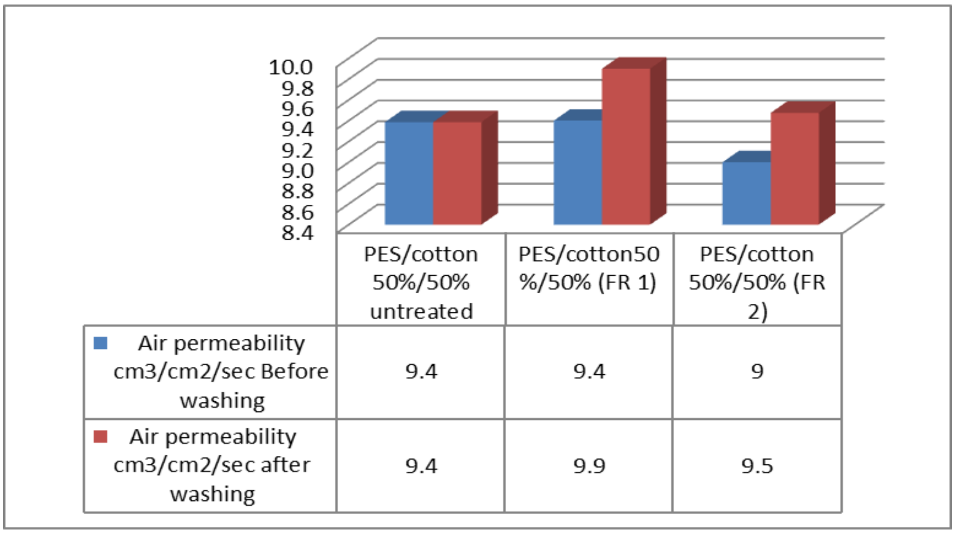


Figure (14).The difference between (FR1) and (FR2) Treatment on water air permeability for 50%PES/50% cotton

The woven fabrics 50%PES/50% cotton sample found that measuring of air permeability for the untreated sample 9.4cm3/cm2 /sec and before washing the treatment with flame retardant treatment doesn’t influence air permeability for the (FR1) treatment sample and cause decrease in air permeability to 9 cm3/cm2 /sec for the (FR2) treatment sample. After washing, the treatment with flame retardant influenced the air permeability cause increase in air permeability to 9.9 cm3/cm2 /sec for (FR1) treatment sample. Also it was a small increase in air permeability to 9.5 cm3/cm2 /sec for the (FR2) treatment samples.

6- The effect of Flame Retardant treatment on fabrics water vapor transmission rate

Table8: Tested fabrics water vapor transmission rate after flame retardant treatment

sample treatment type	water vapor transmission rate g/m^2 before washing	water vapor transmission rate g/m^2 after washing
100% cotton untreated	4.05	4.05
100% cotton (FR 1)	3.45	3.95
100% cotton (FR 2)	4.45	4.85
100% polyester untreated	2.65	2.65
100% polyester (FR 1)	2.25	2.30
100% polyester (FR 2)	2.6	2.45
PES/cotton 50%/50% untreated	4.35	4.35
PES/cotton50%/50% (FR 1)	3.25	3.45
PES/cotton 50%/50% (FR 2)	4.55	3.5

Water vapor transmission rate of a sample is a measure of the passage of water vapor through the sample to the atmosphere. Table 8 shows Water vapor transmission rate of (untreated, (FR 1) and (FR 2) treatment) on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

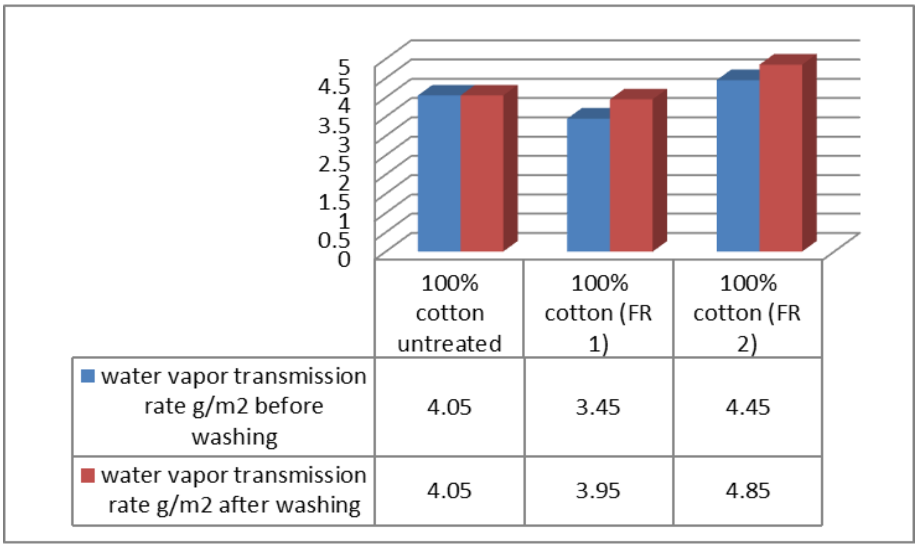
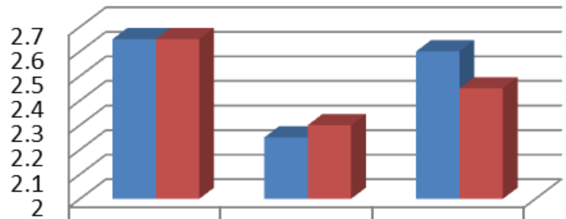


Figure (15).The difference between (FR1) and (FR2) Treatment on water vapor transmission for 100% cotton

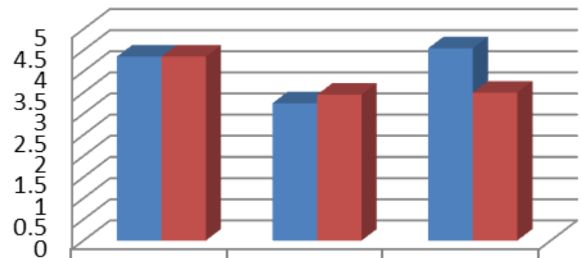
Fig (15) Shows that flame retardant treatment affect woven 100% cotton fabric samples shows that Before washing, the untreated 100% cotton fabric sample has 4.05 g/m2 water vapor permeability, and the 100% cotton (FR1) treatment sample decreased to be 3.45 g/m2 and the sample (FR2) treatment decreased to 4.45 g/m2 . After washing, the untreated 100% cotton fabric sample has 4.05 g/m2 and the 100% cotton (FR1) treatment sample increased to be 3.95 g/m2 water vapor permeability, and the sample (FR2) treatment decreased to 4.85 g/m2.



	100% polyester untreated	100% polyester (FR 1)	100% polyester (FR 2)
water vapor transmission rate g/m2 before washing	2.65	2.25	2.6
water vapor transmission rate g/m2 after washing	2.65	2.3	2.45

Figure (16).The difference between (FR1) and (FR2) Treatment on water vapor transmission for 100% polyester

For 100% Polyester sample (as shown in figure 16) before washing, found that the percentage of water vapor permeability decreased compared to the untreated sample 2.65 g/m2 to become 2.25 g/m2 for 100% polyester (FR1) treatment sample and for the sample 100% Polyester with (FR2) treatment decreased to become 2.6 g/m2 . After washing, both treatment methods cause decreasing in water vapor permeability when compared to the untreated sample which has 2.65 g/m2 so the (FR1) treatment sample decreased to become 2.3 g/m2 and for the sample 100% Polyester with (FR2) treatment decreased to become 2.45 g/m2



	PES/cotton 50%/50% untreated	PES/cotton 50%/50% (FR 1)	PES/cotton 50%/50% (FR 2)
water vapor transmission rate g/m2 before washing	4.35	3.25	4.55
water vapor transmission rate g/m2 after washing	4.35	3.45	3.5

Figure (17).The difference between (FR1) and (FR2) Treatment on water vapor transmission for 50%PES/50% cotton

As shown in figure 17, before washing, the untreated sample water vapor permeability was 4.35 g/m2 and the (FR1) treatment sample decreased to 3.25g/m2 and on contrary for the blended 50%PES/50% cotton sample (FR2) treatment increased in water vapor permeability to 4.55 g/m2. After washing, the untreated sample water vapor permeability was 4.35 g/m2 and the (FR1) treatment decreased in water vapor permeability to 3.45 g/m2 and for the (FR2) treatment sample decreased to 3.5 g/m2.

7- The effect of Flame Retardant treatment on fabrics thermal conductivity

Table9: Tested fabrics thermal conductivity after flame retardant treatment

sample treatment type	thermal conductivity	
	before washing	after washing
100% cotton untreated	2.45	2.45
100% cotton (FR 1)	2.37	2.41
100% cotton (FR 2)	2.31	2.4
100% polyester untreated	2.68	2.68
100% polyester (FR 1)	2.86	2.95
100% polyester (FR 2)	2.7	2.74
PES/cotton 50%/50% untreated	2.73	2.73
PES/cotton50%/50% (FR 1)	3.1	3.2
PES/cotton 50%/50% (FR 2)	3.18	2.9

Thermal conductivity of a fabric is the property of a material to conduct heat to the atmosphere through the fabric. Table 9 shows thermal conductivity of (untreated, (FR 1) and (FR 2) treatment) on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

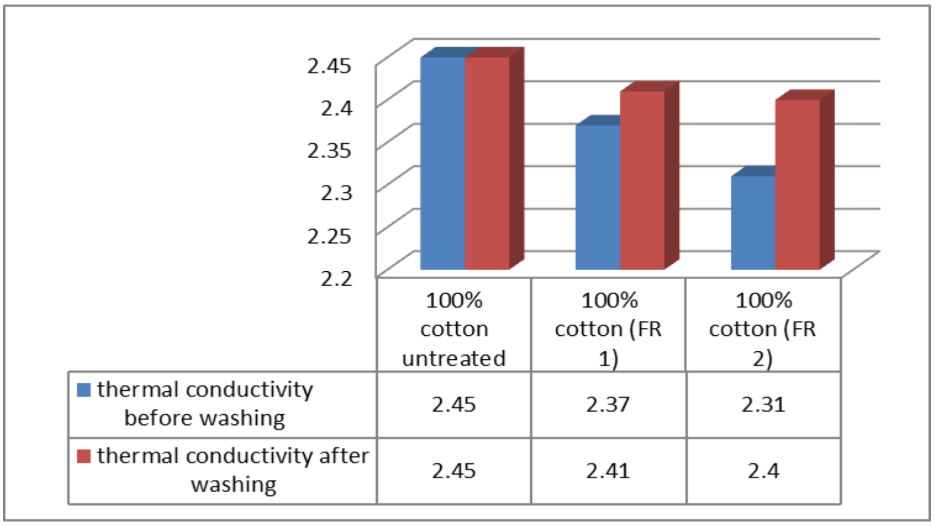


Figure (18).The difference between (FR1) and (FR2) Treatment on thermal conductivity for 100% cotton

Table 9 and fig (18) Shows that flame retardant treatment affect woven 100% cotton fabric samples shows that: Before washing the100% Cotton untreated sample has 2.45 and the 100% Cotton (FR1) treatment sample decrease to be 2.37 thermal conductivity, and the sample (FR2) treatment decrease to be 2.31. After washing the 100% Cotton (FR1) treatment sample decrease to be2.41 Thermal conductivity and the sample (FR2) treatment decreased to 2.4.

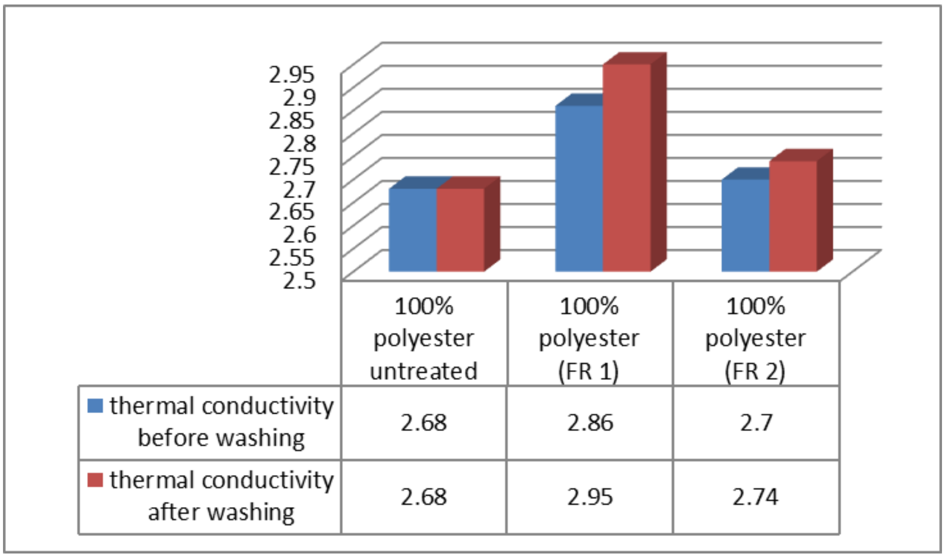


Figure (19).The difference between (FR1) and (FR2) Treatment on thermal conductivity for 100% polyester

for the 100% Polyester samples (as shown in figure 19) before washing found an increase in the thermal conductivity compared to the untreated sample 2.68 to become 2.86 for 100% polyester (FR1) treatment sample and for the sample (FR2) treatment increased to become 2.7.After washing found an increase in the thermal conductivity compared to the untreated sample 2.68 to become 2.95 for 100% polyester (FR1) treatment sample and for the sample (FR2) treatment increased to become 2.74.

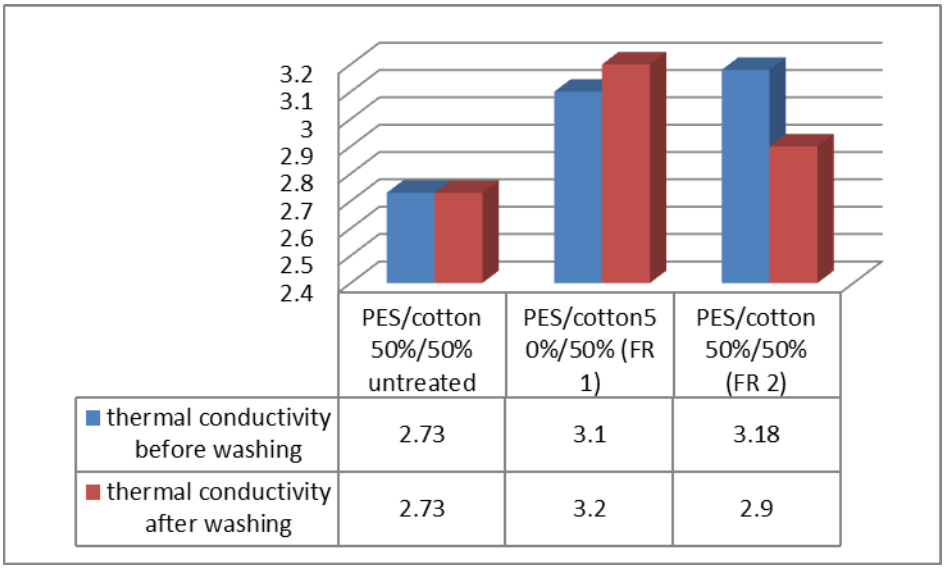


Figure (20).The difference between (FR1) and (FR2) Treatment on thermal conductivity for 50%PES/50% cotton

As shown in figure 20, before washing, the measuring of thermal conductivity for the untreated sample 2.73.Before washing the treatment with flame retardant influenced the thermal conductivity cause increasing to be 3.1 for the (FR1) treatment sample blended and increase the thermal conductivity to 3.18 for the (FR2) treatment sample. After washing found an increase in the thermal conductivity to be 3.2 for the (FR1) treatment sample and decrease the thermal conductivity to 2.9 for the (FR2) treatment sample.

8- The effect of Flame Retardant treatment on fabrics wettability

Table10: Tested fabrics wettability after flame retardant treatment

sample treatment type	wettability sec.	
	Before washing	After washing
100% cotton untreated	43	43
100% cotton (FR 1)	48	40
100% cotton (FR 2)	53	43
100% polyester untreated	108	108
100% polyester (FR 1)	123	83
100% polyester (FR 2)	153	98
PES/cotton 50%/50% untreated	53	53
PES/cotton50%/50% (FR 1)	48	43
PES/cotton 50%/50% (FR 2)	63	49

Wettability is the ability of a liquid to maintain contact with the fabric. Table 10 shows wettability of (untreated, (FR 1) and (FR 2) treatment) on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

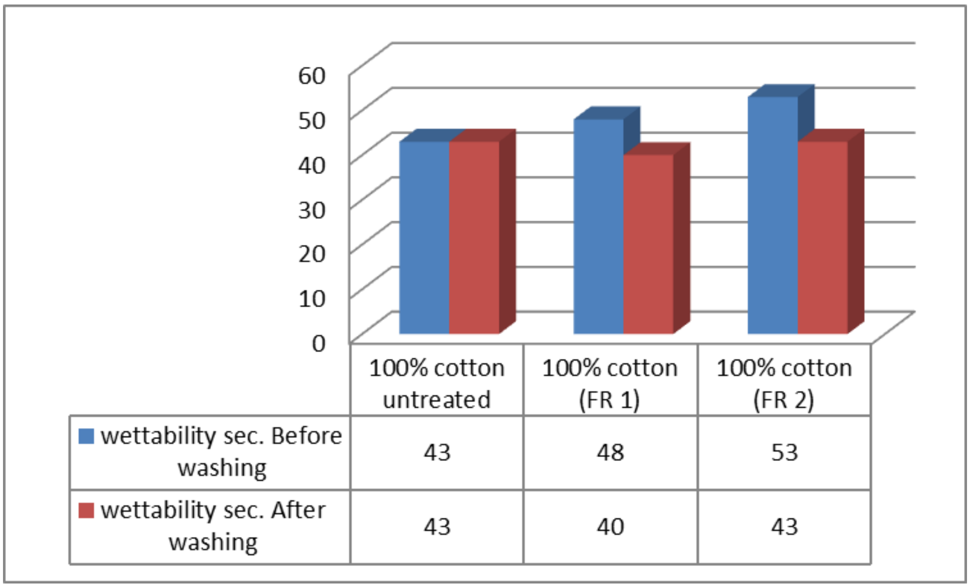


Figure (21).The difference between (FR1) and (FR2) Treatment on wettability for 100% cotton

Table 10 and fig (21) Shows that flame retardant treatment affect woven 100% cotton fabric samples wettability. Before washing, the untreated 100% cotton fabric sample has 43, the 100% cotton (FR1) treatment sample increased to be 48, and the (FR2) treatment increased to 53. After washing, the untreated sample has 43 and the 100% cotton (FR1) treatment sample decreased to be 40, and the (FR2) treatment sample didn’t change.

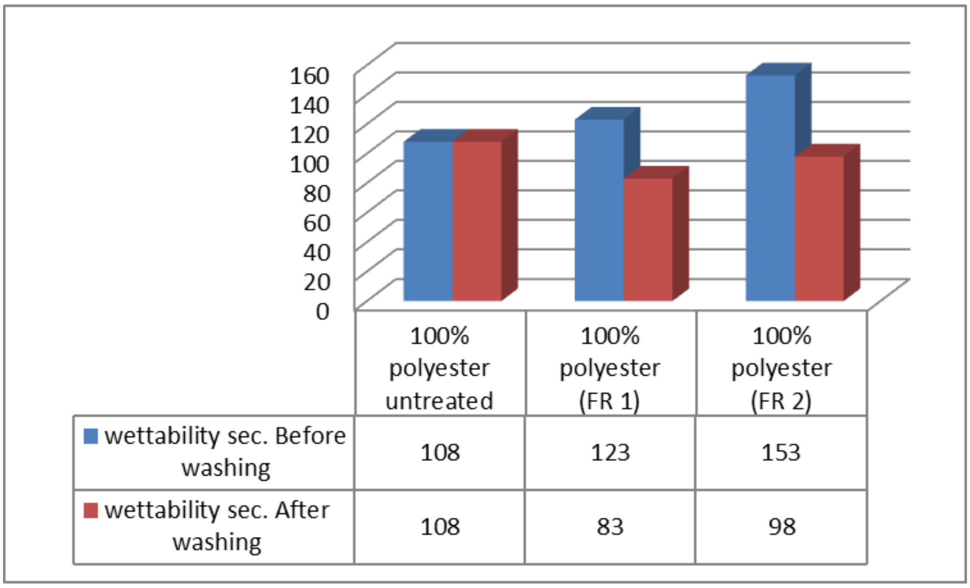


Figure (22).The difference between (FR1) and (FR2) Treatment on wettability for 100% polyester

For 100% Polyester sample (as shown in figure 22), before washing, found that the percentage of wettability increased to become 123 for 100% polyester (FR1) treatment sample and for (FR2) treatment sample increased to become 153. After washing, found a decrease in the percentage of wettability compared to untreated sample 108 to become 83 for 100% polyester (FR1) treatment sample and for (FR2) treatment sample decreased to become 98.

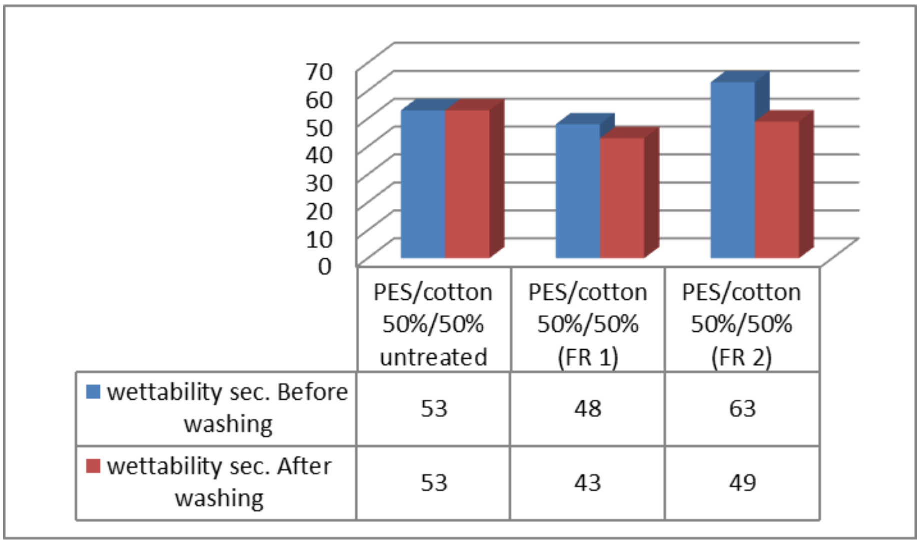


Figure (23).The difference between (FR1) and (FR2) Treatment on wettability for 50%PES/50% cotton

As shown in figure 23, before washing, the untreated sample wettability was 53 and the (FR1) treatment sample decreased to 48 and on contrary for the blended 50%PES/50% cotton sample (FR2) treatment increased in wettability to 63. After washing, the untreated sample wettability was 53 and the (FR1) treatment decreased in water vapor permeability to 43 and for the (FR2) treatment sample decreased to 49.

9- The effect of Flame Retardant treatment on fabrics Rate of burning

Table11: Tested fabrics rate of burning after flame retardant treatment

sample treatment type	Rate of burning (mm/min)	
	before washing	after washing
100% cotton untreated	275.6	275.6
100% cotton (FR 1)	17	19
100% cotton (FR 2)	46	63.5
100% polyester untreated	387.5	387.5
100% polyester (FR 1)	35	38.3
100% polyester (FR 2)	51.4	67
PES/cotton 50%/50% untreated	342.8	342.8
PES/cotton50%/50% (FR 1)	26.5	31
PES/cotton 50%/50% (FR 2)	73.2	94.7

Rate of burning of a sample denotes that it doesn't propagate flame, although it may burn or char when subjected to sufficient heat mechanism. Table 11 shows rate of burning of (untreated, (FR 1) and (FR 2) treatment) on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

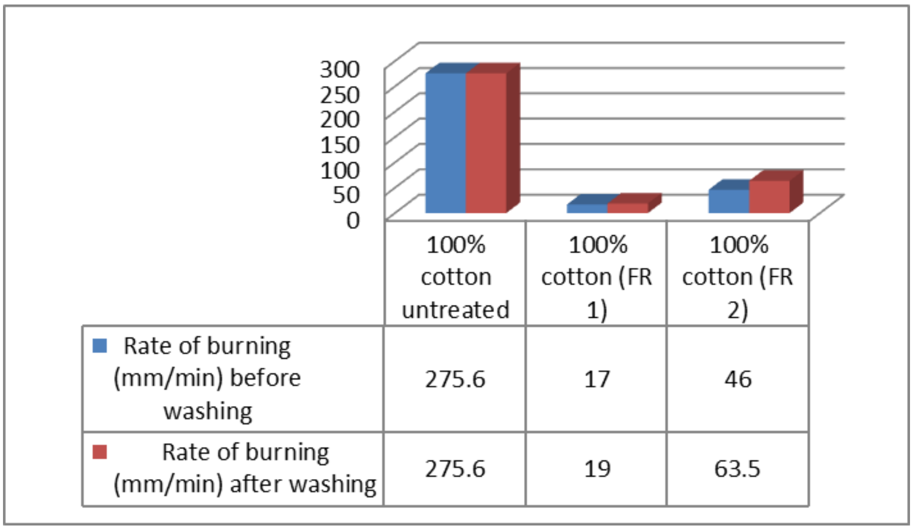


Figure (24).The difference between (FR1) and (FR2) Treatment on Rate of burning for 100% cotton

Table 11 and fig (24) Shows that flame retardant treatment affect Rate of burning of woven 100% cotton fabric samples shows that: Before washing the100% Cotton untreated sample has 275.6 and the 100% Cotton (FR1) treatment sample decrease to be 17, and the sample (FR2) treatment decrease to be 46. After washing the 100% Cotton (FR1) treatment sample decrease to be 19 and the sample (FR2) treatment decreased to 63.5. This can be explained by the flame retardant particles which coated the cotton fibers and penetrate them. And it has a very significant effect in reducing Rate of burning.

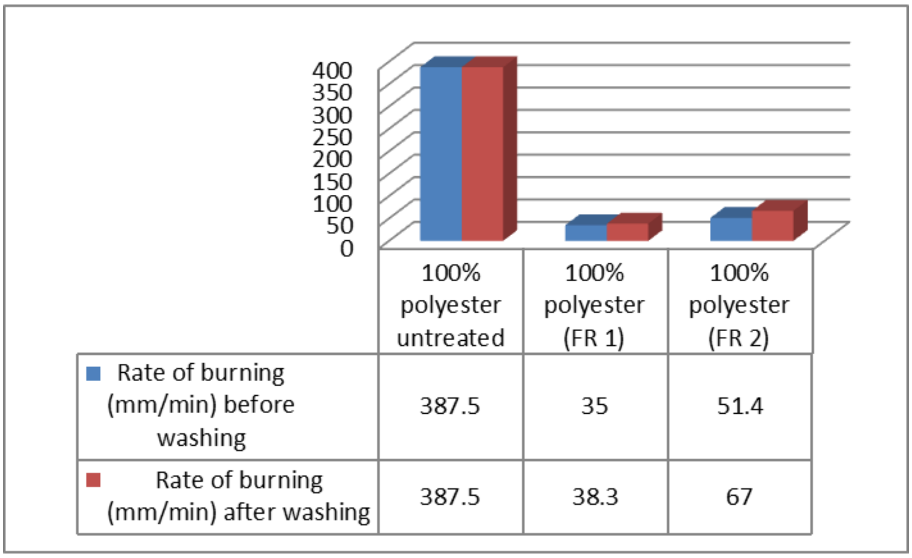


Figure (25).The difference between (FR1) and (FR2) Treatment on Rate of burning for 100% polyester

For 100% Polyester sample (as shown in figure 25), before washing, the Rate of burning decreased to become 35 for the (FR1) treatment sample and for (FR2) treatment sample decreased to become 51.4. After washing, the Rate of burning decreased compared to untreated sample 387.5 to become 38.3 for the (FR1) treatment sample and for (FR2) treatment sample decreased to become 67. This shows that the flame retardant finished woven fabrics by PF-phosphorus / nitrogen compound based has the best Rate of burning which is more durable after washing.

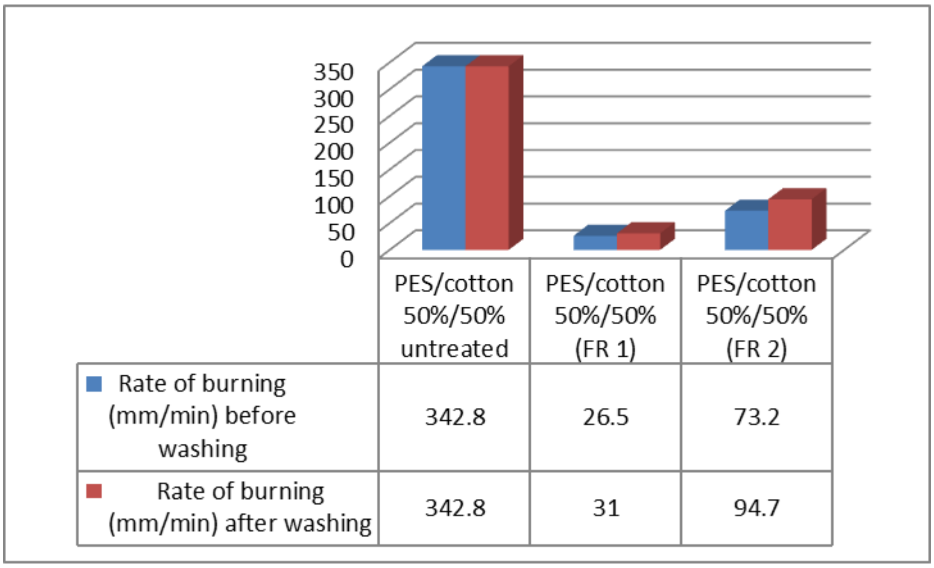


Figure (26).The difference between (FR1) and (FR2) Treatment on Rate of burning for 50%PES/50% cotton

As shown in figure 26, before washing, the untreated sample Rate of burning for 50%PES/50% cotton was 342.8 and the (FR1) treatment sample decreased to 26.5 and the blended 50%PES/50% cotton sample (FR2) treatment decreased to 73.2. After washing, the (FR1) treatment sample Rate of burning decreased to 31 and for the (FR2) treatment sample decreased to 94.7. This explains that the treatment with PF-phosphorus / nitrogen compound based is more stable and durable after washing.

10- The effect of Flame Retardant treatment on fabrics Infra-Red (IR):

Infra-Red (IR) used to study the chemical composition and structural morphology of the untreated and treated samples with (FR1) treatment on different woven fabric as 100% cotton, PES/cotton50%/50% and 100% polyester.

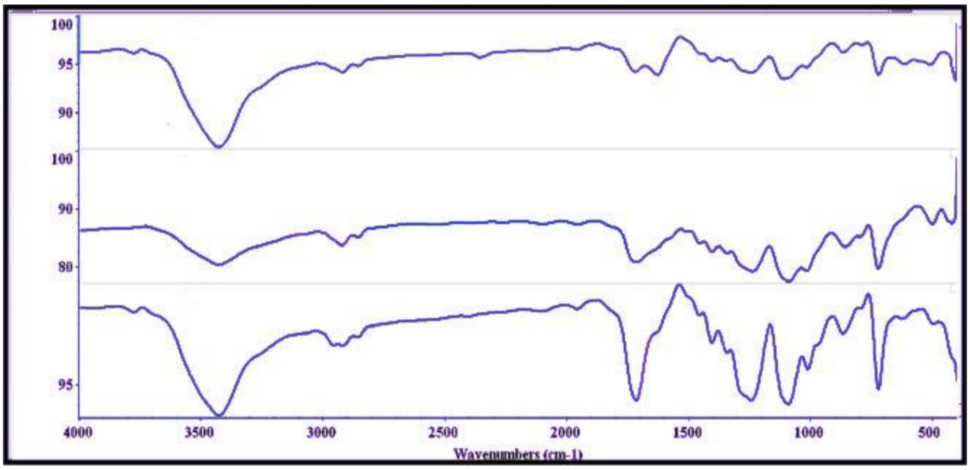


Figure (27) IR spectrum of different untreated woven fabric (100% cotton, PES/cotton50%/50% and 100% polyester)

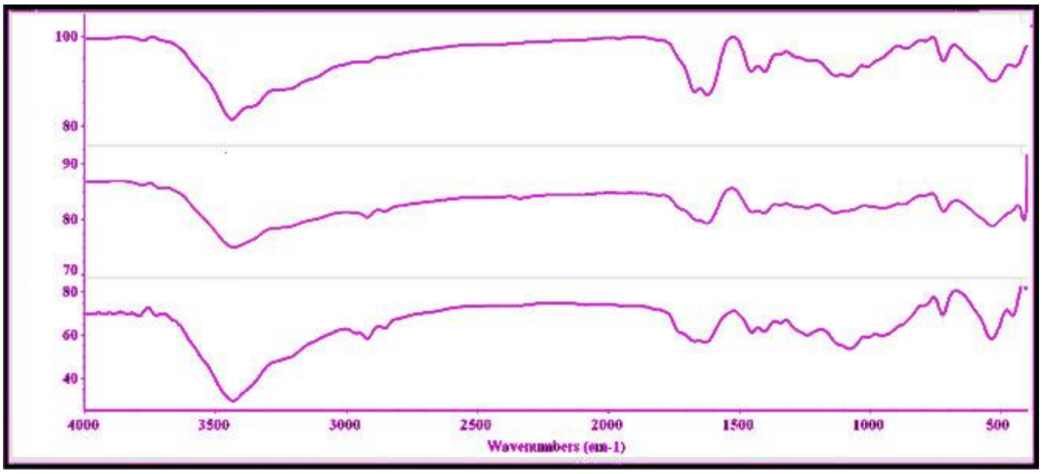


Figure (28) IR spectrum of different treated woven fabric (100% cotton, PES/cotton50%/50% and 100% polyester) with (FR1) treatment.

The two figures (27,28) illustrate that, the band at 3440 cm−1 is related to stretching vibrations of —OH group in the case of cotton sample. As can be seen from the spectra of 100% Polyester and 50%PES/50% cotton sample, the stretching vibrations of OH group were decreased to 3434 and 3438 cm−1 for 100% Polyester and 50%PES/50% cotton, respectively. The bands in the range of 2800–3200 cm−1 corresponded to stretching vibrations of C—H groups like CH2 and CH3. Strong —CH and —CH2 stretching vibrations between 2930 and 2940 cm−1 have also been observed. This figure included 3220 (N–H), 1243 (P = O), 1084 (P–O symmetric vibration), 868 (P–O asymmetric stretching vibration), and 796 cm−1 with intensities of 86.728%, 96.283%, 92.089%, 96.018%, and 95.092%, sequentially.

4. Conclusion:

1- The two different flame retardant treatments have a significant effect on performance and functional properties.

2- This study shows that the PF-phosphorus / nitrogen compound based treatment gives the best results for fire-fighter suit fabrics, with fiber content of 100% cotton, 50%PES/50%

cotton and 100%PES, and more durable than the PR 20-organo phosphorus-based, therefore (FR1) treatment are more safer for the fire-fighter, economical and environment.
3- From the IR analysis we could observe different absorption peaks for the PF-phosphorus / nitrogen compound based treatment In comparison with samples before treatment.
4- The increase in weight loss with washing of the flame retardant fabrics also shows washing of the FR-finish fabrics causes' considerable loss of flame retardant finish. And the PF-phosphorus / nitrogen compound based treatment is more stable than the PR 20-organo phosphorus-based.
Thus, the flame retardant treatments for (FR1) treatment and blended 50%PES/50% cotton woven fabric is proved to have better durable flame retardant fire-fighter suit.

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