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Radiative and thermal characterization of basalt fabric as an alternative for firefighter protective clothing

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ABSTRACT

This work investigates the thermal performance and characterization of Basalt Fiber as an alternative for firefighter protective clothing at elevated temperature. The development of protective clothing for better protection, stability, and durability has been the subject for several researches. Since the main mechanism or heat transfer between fire and firefighter is radiation, therefore produce the second degree of burn in the firefighter, Ultraviolet Visible near Infrared (UV-vis-NIR) spectrophotometer was used, toperform the thermal radiation. Basalt and Glass fabric coated with aluminum foil and uncoated were used for comparison the thermal properties. Chemicals bonding and molecular structure that cause higher thermal stability of basalt fiber were identified using FTIR, while low thermal degradation was performed using TGA. Significant improvement in reflection was observed in the fabrics after coating with aluminum foil. The main difference was in the surface roughnessof the materials, also basalt revealed to be natural resistant to electromagnetic radiation. FTIR result showed greater Q^4Si-O molecular networking and chemical bonding for basalt fiber, thus higher thermal stability, because according to TGA results only 0.58% of mass was lost at elevated temperatures.(900^{o}C) Thermal performance and characterization of basalt fiber in this investigation suggest that basalt fiber possess excellent thermal performance and stability at elevated temperature, with great potential for application in firefighter protective clothing.

KEYWORDS

Basalt Fiber;
Radiactive;
Thermal Performance;
Firefighter Protective.

INTRODUCTION

Recent reports show that millions of people worldwide are exposed to various thermal environments, particularly the firefightersand their bodies need protection. The performance requirements of protective clothing for firefighters often demand the balance of widely different properties, such as thermal resistance, oxidative stability, and good mechanical performance.

Firefighter Protective Clothing against thermal exposure is ofcrucial importance for firefighters in the line of duty because it must provide enough protection and comfort against intense radiation heat flux which normally ranges from 6 kW/m^2 up to 84 kW/m^2 or even more. The radiative heating load depends on the source of radiation and the reflectance of the surface receiving the radiation. Previous reports explain that the primary mechanism of heat transfer between the fire and firefighter is 70% radiation, and the other 30% is divided between conduction and convection[1]. The reflectance of the fabricmainlydepend on the fiber material, roughness and coating.[2].

Recentlyreports have shown that Basalt a novel fiber, considered, the 21th century fiber has excellent thermal, physical, and mechanical properties at elevated temperatures. In this research Basalt fabric is studied as an alternative as high performance fibers, with potential application in the firefighter protective clothing.

Thermal Performance for firefighter protective clothing has been widely studiedfor many years[3-8]. Basicallyfirefighting protective clothing is designed to protect to the firefighters skin againstfrom burns,therefore is crucial importance plays the material of firefighting protective clothing to provide effective protection during thermal exposures

The thickness and the fabric construction have a stronger influence[9,10]while the color of the fibers have different ability to absorb UV radiation and to block most of the incident radiant energy and prevent it from reaching the skin. The reason is because yarn color, additives and coatings have much more significant impact on UV transmission properties rather than fiber composition itself.[11]

Result of fiber surface morphology and mechanical properties of basalt fiber hasbeen extensively studiedfor wide application in composite, reinforcement material[12-14], butlittle information is available on the thermal propertiesand applicationsspeciallyforfirefighter protective clothing. Destructivetest such as Thermogravimetric Analysis (TGA) and nondestructivetest Ultraviolet Visible Near Infrared spectrophotometer (UV-vis-NIR), and Fourier Transform Infrared (FTIR) testareused in this investigation.

The main objective was to investigate and compare the thermal performance of Basalt and fiberglass, as an alternative, in the construction of firefighting protective clothing and future applications, when the temperature reach 700^{o}C or more. At that temperature normally conventional high performance fibers (HPFs) lose their properties due to the high heat fluxes, as well as the high cost that implies.

MATERIALS AND METHODS

Continuous Basalt Fiber and fabric was purchased from Jiansu TianLong Continuous Basalt Fiber Hi-Tech Co. Lda., and aluminium foil was purchased from Shanghai Shenhuo Aluminium foil Co, Ltd.

The thermal performance ofcoated and uncoated Basalt and Glass fabrics were analyzed, the coating material was aluminum foil, the set of fabric properties tested are summarized in TABLE 1

Ultraviolet near infrared spectrophotometer (UV-VIS-NIR)

TABLE 1 : Basic Properties of the Materials

Material	Structure	Fabric Count (10 x 10 mm)	Thickness [mm]	Area Mass [g/m^2]
Coated Basalt	Plain	19 x 10	0.625	780.12
Coated Glass	Plain	12 x 8	0.963	499.02
Basalt Uncoated	Plain	19 x 10	0.614	780.00
Glass Uncoated	Plain	12 x 8	0.952	499.02
Al Foil	-	-	0.011	29.7

The dominant heat transfer mode between fire and clothing surface is radiation, (about 70%), the other heat transfer mechanisms such as convection and conduction are neglected as they represent a small quantity For the present research, small square woven samples with dimension 6 x 6 [cm] were cut, and then held in the detector at scan speed of 750 nm/mint, with wavelength range between 2600 nm to 240 nm, a UV-Vis-NIR spectrophotometer, HITACHI, was used for this purpose

Fourier transform infrared spectroscopy (FTIR)

FTIR investigations of inorganic fibers (basalt and glass) weretested onThermo Nicolet Spectrometer. Basalt and glass fabrics were cut in small pieces with 2 x 7 cm of dimension. The samples were inserted in the spectrometer and spectrum was recorded from 4000 to 500cm^{-1}with aresolution of 4 cm^{-1}. The FTIR spectra was collected at 65±2%RH and 21±1^{o}C environmental conditions.

Thermogravimetric analysis (TGA)

For TGA tests approximately 4 mg in average of basalt and fiber glass samples were placed in pan, and the temperature was set from 50°C up to 900°C, onset temperature, maximum mass loss temperature, and final temperature respectively were quantified, using termogravimetric instrument Netzsch *TG 209F1* with a heating rate of 10°K/mint, in Nitrogen Atmosphere.

RESULT AND DISCUSSION

In this section the result obtained after evaluation of thermal performance of Basalt and Fiberglass, destructive test are given and discussed.

Ultraviolet near infrared spectrophotometer (UV-near-VIS) result.

The radiation is one of the major causes of degradation of textile materials, which is due to excitations in some parts of the polymer molecule and a gradual loss of integrity, and depends on the nature of the fibers. The penetration of the thermic radiation in the textile materials usually causes photo oxidation and results in decrease in elasticity, tensile strength and a slight increase in the degree of crystallinity. The radiation at Elevated temperature result in severe loss of the properties in most cases in the textile fabrics. Similar to homochain polymers there areseveral hetero chain polymers also that are highly susceptibleto photo degradation: polyesters, polyamides and polyaramids,polyethers, polyimides, polyurethanes and polysulphides and also highstrengthfibersn such as:zylon, dyneema and Kevlar losses strength upon exposure to radiation.

The surface of textile fabrics is never absolutely ûat and smooth, and fabrics are rarely balanced in terms of the appearance of warp and weft on their surface. Even in the case of plain weave fabrics, there is often a dominance of one group of threads on the surface, resulting in the other type of thread being hidden. This introduces complications into obtaining structural information from surface roughness data.

The reflectance spectrum in Visible and Near infrared region of Glass fabric and Basalt is shown in the Figure 1, as can it is observed, coated glass fabricexhibit higher reflectance around 74.49% in average in the Visible region and 72.25% for coated basalt fiber, which means Glass fiber is 2.49% more reflective than basalt fabrics, this is attributed to the roughness surface of the samples.

As it was mentioned before mainly the difference is because of three factors affecting the reflectance properties in textile fabrics, the roughness of the surface, the natural light color of fabric, and the coating with aluminum foil.

Since Glass fabric has a light (white) color it reflects more than basalt. Coating with aluminum foil contribute at least 90% to the reflectance due to the specular (glossy) surface and also give smooth surface, compare with coated Basalt the difference is 14.57% in the visible region and 15.72% in the near infrared region.

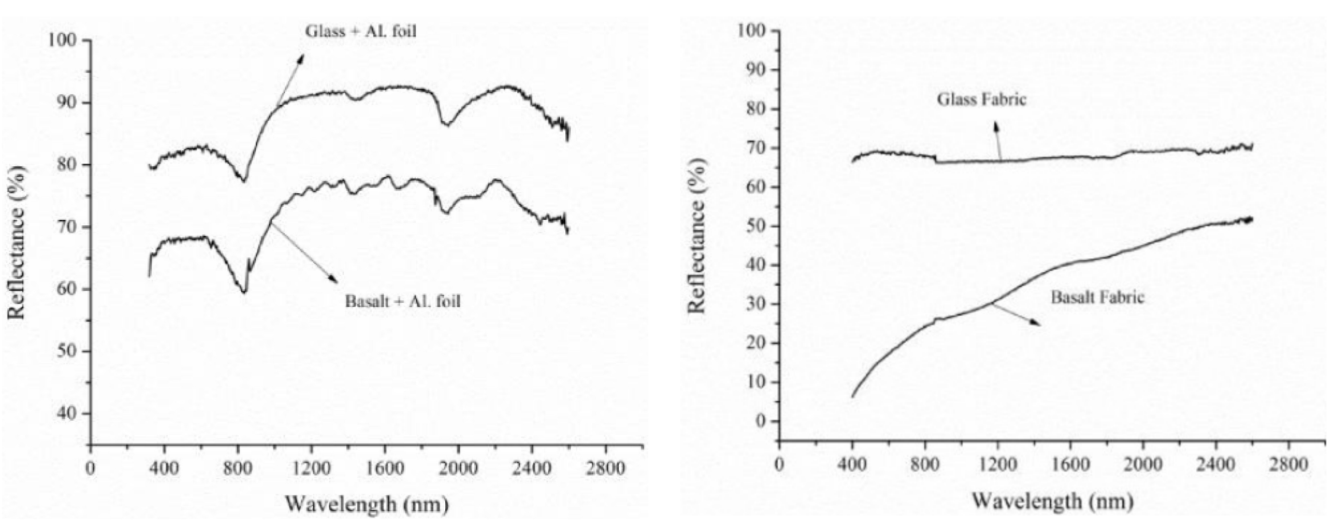

Figure 1 : Reflectance spectrum of Glass and Basalt Fabric

On the other hand compare with uncoated basalt fabric which has a golden brown color and naturally UV and it has high electromagnetic radiation resistance than glass fabric, the difference is around 15.84%

Particularly in personal protection, the vapor penetration must be lower because 75¼g/m^3 for one hour is enough to produce blister in the human skin, since coated glass and basalt reveals possess good reflectivity properties.

In terms of transmittance uncoated basalt fabrics shows better result therefore it offers more safety due to the higher absorbance of electromagnetic radiation.

TABLE 2 is summarized the average reflectance of Glass and Basalt fabric.

TABLE 2 : UV-NIR Values of Glass and Basalt Fabrics

Sample	Fabric Construction	VIS [%]	NIR [%]
Coated Basalt	Plain	67.44	73.71
Coated Glass	Plain	82.01	89.43
Uncoated Basalt	Plain	15.64	39.57
Uncoated Glass	Plain	68.48	68.23

Fourier transform infrared (FTIR) characterization

Since both glass fiber and basalt fiber are inorganic materials, that possess anions of oxygenated system while is an important feature of inorganics compound, the main difference with organic spectra is that inorganics compounds has a fewer spectral absorption bands. Therefore the analysis of complex mixtures are limited that is why infrared analysis of inorganic materials have not been as popular as analysis of organic.[15]. Figure 2, it is shows the FTIR spectra for both glass and basalt fibers, both coated with aluminum foil

The IR spectra of basalt and glasshave been conducted. Researchers noted that different spectralregions correspond to vibrations of different structuralunits, and claimed that the bands within1200–1100 cm^{-1}are due to the stretching vibrations ofnon-bridging bonds in

s tetrahedral that contain onenon -bridging oxygen atom. Thebands with peaks at 1053 cm^{-1}are associate with the vibrations of terminal groups in tetrahedral containing three and sometimes two non-bridging

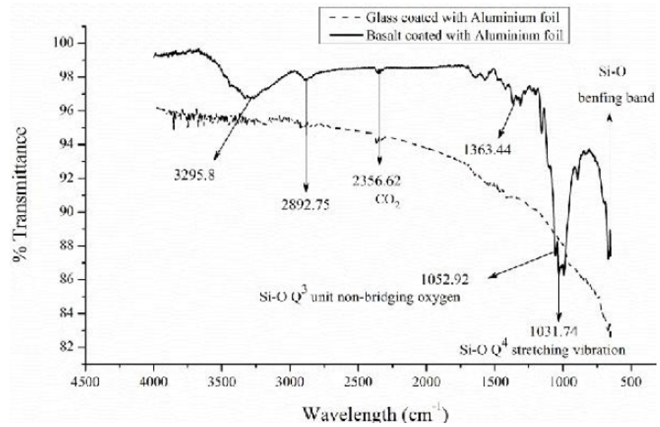

Figure 2 : FTIR spectra of Basalt and Glass coated fabrics

oxygenatoms.

As it is well known the covalent Si-O has enthalpy bond of 466 kJmol^{-1}, compared with the C-C bond which has a bond enthalpy of 347 kJmol^{-1}, this mean that the linkage -Si-O-Si-O- is very stable

In basalt fiber absorption spectrum SiO_2 stretching

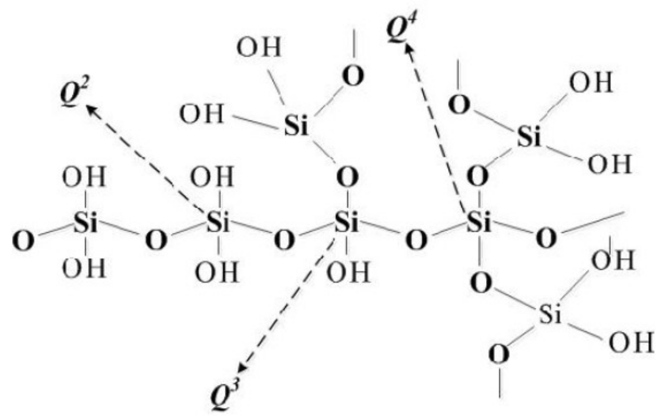

Figure 3 : Schematic representation Si-O Molecular networking in inorganic fibers

band was located in the range of1000 – 1050 cm^{-1} which is the most intense absorption, and this anion is assumed to consist of Q^4 species forming a continuous random network, the position of the main Si–O–X stretching band (X = Si, O, or OH) gives an indication of the length and angle of the bonds in a silicate network. In the TABLE 3 are more details is presented.

Due to formation of covalent bond Si-O with higher

TABLE 3 : Absorption Spectra of Basalt and Glass Fabric

Fabric	A_{set}	M_{abs}	A_{end}
Basalt	0.004	0.062	0.058
Glass	0.017	0.055	0.082

enthalpy bond than other molecular bond formation, basalt fiber shows greater Si-O networking (Q^2,Q^3, and Q^4) this contributes in better thermal and mechanical performance than Glass fiber, these advantageous properties make basalt fabric one of the most promising textile fabrics for firefighter protective clothing.

Thermogravimetric analysis TGA

Glass andcontinuous basalt fiberare prepared from mineral compounds, containing mainlyAlumina in Silicate glasses is known to play the dual role of the glass former.

The thermo gravimetric (TG) traces for Basalt and Glass fiber performed in nitrogen atmosphere at 10°K/mint heating rates are presented in Figure 4

Figure 4, shows that both fiber Basalt as well Glass,

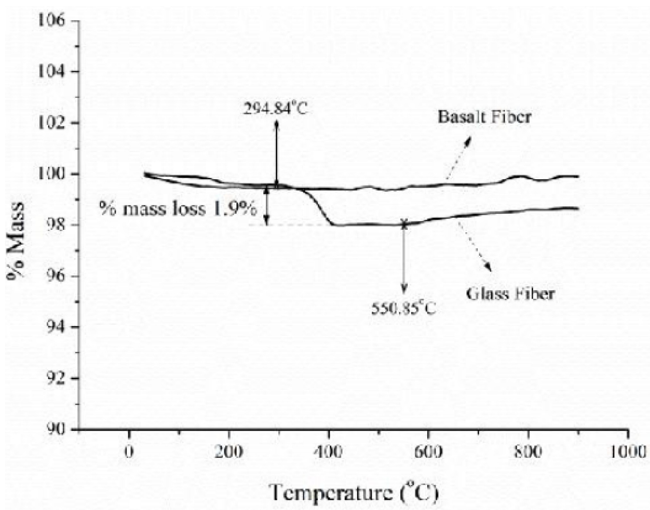

Figure 4 : TG of Basalt and Glass fiber

undergoes thermal degradation, and it occur simultaneously, it is apparent from the inception both samples start losing weight, before onset temperature, although the degradation ratio is low.

In the case of Basalt Fiber thedegradation is almost imperceptible, while glass fiber performs a notorious degradation between, 330°C – 420°C. Quantitative data, the onset degradation (T_{onset}), the temperature maximum (T_{max}), end temperature of degradation (T_{end}), have been calculated from the DTG plot, and it is summarized in the TABLE 4

The onset degradation temperature of Glass fiber occur at 294.85°C, in the next 82.56°C reach the maximum mass loss, and in this step 1.9% of the original mass was loss, and then in the next step up to 550.85°C,

TABLE 4 : TG Analysis of Basalt and Fiber Glass

Sample	T_{onset} [°C]	T_{max} [°C]	T_{end} [°C]	ΔT [°C]	Mass Loss [%]
Basal Fiber	271.14	359,64	451.26	180.12	0.58
Glass Fiber	294.85	377.41	454.35	159.5	1.9

the mass of the glass fiber remained constant. The same phenomenon happens with basalt fiber, although the onset, maximum and end temperature is quite similar to the glass but, only 0.58% from the original mass was lost asmaximum, and then the mass remained constant

A slight increase in the weight is observed beyond 600°C, in both fibers because at high temperature normally there is formation of nitrides [16,17]due to the reaction with nitrogen environment.

In comparison basalt fiber has a better thermal performance than glass, is due to the Q^4 molecular structure of silicon which means it has better cristallinity and molecular alignment, therefore more energy isrequired to break the existing bonds. This make to basalt fiber better thermal and mechanical performance than glass fiber.

CONCLUSION

Basalt fiber as novel materials was characterized using UV-vis-NIR. FTIR and TGA test, for future application in the protective clothing at high heat fluxes, therefore elevated temperatures. It exhibited excellent, radiative, thermal stability properties, either coated or uncoated, although the difference was mainly because of coating material such aluminum foil and the roughness of the fabric surface. The result obtained from the FTIR, despite little information is available in the literature, suggest that the greater thermal and stability of basalt fiber than glass fibers is due to the higher Q^4 Si-O molecular structure which require higher energy to break therefore higher thermal and mechanical energy is needed to separated them.

The result of TGA illustrates lower degradation for Basalt fiber, although it begins to degrade at early thermally thus, and mass loss. The decomposition of basalt was less than 0.6%, making it good enough for protective clothing.

REFERENCES

[1] N.J.Abbott, S.Schulman; Protection From Fire: Nonflammable Fabrics and Coatings, Journal of Industrial Textiles, **6**, 48-64 **(1976)**.

[2] J.Quientiere; Radiative Characteristics of Fire Fighters' Coat Fabrics, Fire Technology Division National Bureau of Standards, **3**, 153-161 **(2009)**.

[3] A.C.Bengi Kutlu; Thermal Analysis and Performance Properties of Thermal Protective Clothing, FIbres & Textiles in Eastern Europe, **13**, September **(2005)**.

[4] M.Day, P.Z.Sturgeon; Thermal radiative protection of fire fighters' protective clothing, Fire Technology, **23**, 49-59 **(1987)**.

[5] G.S.Hwa Sook Yoo, Ning Pan; Thermal Protective Performance an confort of Wildland Firefighter Clothing The transport Properties of Multilayer Fabric Systems, Amercina Society for Testing ang Materials,**7** **(2000)**.

[6] L.Jin, K.-A.Hong, H.D.Nam, K.J.Yoon; Effect of Thermal Barrier on Thermal Protective Performance of Firefighter Garments, Journal of Fiber Bioengineering and Informatics, **4**, 245-252 **(2011)**.

[7] F.L.Zhu, W.Y.Zhang; Evaluation of Thermal Performance of Flame-resistant Fabrics Considering Thermal Wave Influence in Human Skin Model, Journal of Fire Sciences, **24**, 465-485 **(2006)**.

[8] R.L.Barker; Effects of Moisture on the Thermal Protective Performance of Firefighter Protective Clothing in Low-level Radiant Heat Exposures, Textile Research Journal, **76**, 27-31 **(2006)**.

[9] K.S.Ma³gorzata Matusiak; Influence of the Structure of Woven Fabrics on Their Thermal Insulation Properties, Fibres & Textiles in Eastern Europe, **19**, 46-53 **(2011)**.

[10] L.Hes, M.De Araujo, V.V.Djulay; Effect of Mutual Bonding of Textile Layers on Thermal Insulation and Thermal Contact Properties of Fabric Assemblies, Textile Research Journal, **66**,.245-250, April 1 **(1996)**.

[11] R.U.Helena Gabrijelèiè, Franci Sluga, Krste Dimitrovski; Influence of Fabric Constructional Parameters and Thread Colour on UV Radiation Protection, FIBRES & TEXTILES in Eastern Europe, **17**, 46-54, March **(2009)**.

[12] J.Sim, C.Park, D.Y.Moon; Characteristics of basalt fiber as a strengthening material for concrete structures, Composites Part B: Engineering, **36**, 504-512 **(2005)**.

[13] B.Wei, H.Cao, S.Song; Environmental resistance and mechanical performance of basalt and glass fibers, Materials Science and Engineering: A, **527**, 4708-4715 **(2010)**.

[14] V.Manikandan, J.T.Winowlin Jappes, S.M.Suresh Kumar, P.Amuthakkannan; Investigation of the effect of surface modifications on the mechanical properties of basalt fibre reinforced polymer composites, Composites Part B: Engineering, **43**, 812-818 **(2012)**.

[15] R.A.F.a.J.A.Queiser; Inorganic and Organic Analysis by Infrared Spectrometry in Coal Problems, U.S.Department of the Interior,Bureau of Mines, Pittsburgh Coal Research Center, Pittsburgh, Pa..

[16] B.Wei, H.Cao, S.Song; Degradation of basalt fibre and glass fibre/epoxy resin composites in seawater, Corrosion Science, **53**, 426-431 **(2011)**.

[17] P.K.Roy; Thermal degradation studies of LDPE containing cobalt stearate as pro-oxidant, eXPRESS Polymer Letters, **1**, 208-216 **(2007)**.