# THE EXPERIMENT DETERMINATION OF THE OPTIMAL MIXING RATIO OF POLYESTER FIBER SCRAP WITH 100% POLYESTER IN NONWOVEN FABRIC PRODUCTION

Nattavadee Mahanil

Department of Industrial Engineering Technology, Faculty of Digital Technology and Innovation
Southeast Bangkok University
Corresponding author email: nattavadee.m@gmail.com

Received: July 12, 2023
Revised: September 8, 2023
Accepted: September 19, 2023

**Abstract**

The purpose of this research is to study the optimum ratio between polyester fiber scraps and virgin polyester. In the study, the production process of a nonwoven fabric manufacturer in Rayong, Thailand, it was found a problem in the production process, there is a large amount of polyester fiber scrap left from the production process. Therefore, the waste of polyester fiber from the production process was mixed with pure polyester raw material in 4 sets of ratios, namely 4:96, 6:94, 8:92, and 10:90 get to average to compare with the conditions weight values, strength, elongation, and thickness as to the testing standards by TIS no. 121 and analyzing process capability by the Actual Process Capability Index (Cpk) was used by analyzing and processing from the Minitab package to examine the variability of the production process. The results showed that the ratio was 4:96 with a mean total weight of 27.5 grams per square meter. The thickness value was 1.07 mm., the strength value was 25.85 N.m., and the elongation value was 5.05 N.M., which were in the specified criteria for all test results. The ratio was 6:94 with an average weight of 27.9 g/m. square meter The thickness value was 1.10 mm., the strength value was 24.41 N.m., and the elongation value was 4.40 N.M., were within the specified criteria for all test results and both of which had a Cpk greater than 1, indicating that the process was capable or there is a natural variance. After the improvement in the past 12 months, it was found that the amount of poly fiber scrap 58 tons of ester left over from the production process were recycled and 45 tons were recycled, representing 77.58% of the recycled polyester scrap or the efficiency of the product was 96.7

**Keywords:** Polyester, Nonwoven Fabric, Optimal Ratio, Scrap, Reuse

## 1. Introduction

Textile and garment industry is a large-scale manufacturing industry with fully integrated manufacturing structure, consisting of sub-industries in manufacturing process like upstream sector, i.e., fiber production and spinning to mid-stream sector, i.e., weaving, knitting, nonwoven fabric, dyeing, printing, finishing and to downstream sector, i.e., designing and adding higher value to be ready-made clothes or other ready-made garments. Textile and garment industry is important to Thailand in terms of export revenue and huge labor employment. There are 4,829 textile and garment factories, around 460,000 employees, and investment fund of 205,600 million baht [1]. However, during the end of 2019, the world and Thailand confronted the pandemic of Coronavirus of Covid-19, contributing to changes in every industry. Recently, at the beginning of 2020, manufacturers and distributors needed to suspend their businesses or reduced production capacity caused by preventive measures taken by the government for Covid-19. Meanwhile, the spread in foreign countries increased continuously, making the value of textile and garment exports across the world declined. In Thailand, the cumulative export in the first half of 2020 decreased continuously by 16.9% on average as many fashion brands cancelled or postponed factory orders [2]. According to the study on problems in manufacturing process of a company in Rayong province, in terms of nonwoven fabric manufacturing, 100% polyester fabrics were imported abroad to be a raw material in the manufacturing, a problem occurred due to importation of raw materials necessary for manufacturing process. A ratio of polyester fabric scraps after manufacturing process as seen in Table 1.

**Table 1** The ratio of polyester fabric scraps (percent) after manufacturing process for 12 months.

| Month | Ratio (%) | Month | Ratio (%) |
|---|---|---|---|
| January | 6.5 | July | 8.3 |
| February | 7.0 | August | 6.1 |
| March | 6.7 | September | 6.2 |
| April | 6.7 | October | 6.6 |
| May | 6.9 | November | 6.3 |
| June | 6.2 | December | 7.0 |
| Ratio Average = 6.71% per Month | | | |

From Table 1, the researcher had an idea to reuse polyester fabric scraps in the manufacturing process so as to reduce the cost of raw materials. However, the reuse of polyester fabric scraps that passed manufacturing process requires the mixing with 100% polyester fabric to ensure products shall meet the standards. Therefore, this research aimed to study the optimal mixing ratio between polyester fabric scraps from the manufacturing process and 100% polyester fabric. Independent variable was the mixing ratio between polyester fabric scraps from the manufacturing process and 100% polyester fabric and dependent variable was properties of nonwoven fabrics compliant to standards. 4 ratios in the experiment were 4:96, 6:94, 8:92 and 10:90, obtained from the review of relevant literature [3-5] and trials at the beginning for being able to determine the mixing ratio. Consideration was given to the optimal mixing ratio to be used for adjusting the mixing ratio in the manufacturing process to achieve worthiness of raw materials used and to reduce operating costs.

## 2. Literature Review

Shobha Rani Nadupuru, R.K. Jain, Deepa A. Joshi and Radhika Menon (2022) had study Experimental Analysis using Polypropylene, Polyester and Waste Denim Fiber in Road Construction. A method for mixing polypropylene, polyester, and waste denim fiber with bitumen was developed in this study, which resulted in uniform fiber dispersion. The Optimum Binder Content (OBC) and Optimum Fiber Content (OFC) are calculated using the Marshall Procedure. Preparing asphalt concrete mixtures with the required fiber dosages ranging from 5 to 15% by weight of binder enables for extensive laboratory testing. The volumetric parameters of the mixes, as well as strength tests such marshall stability, are determined. [6]

Yafeng Gong, Jiaxiang Song, Haipeng Bi and Zhenhong Tian (2020) had study Optimization Design of the Mix Ratio of a Nano-TiO2/CaCO3-Basalt Fiber Composite Modified Asphalt Mixture Based on Response Surface Methodology based on the Box–Behnken method and the response surface method, a three-factor and three-level test was designed. The test results show that the optimal contents of NTC and BF and the optimal asphalt–aggregate ratio were 5.1%, 3.9%, and 5.67%, respectively. By comparing the measured Marshall test index value with the predicted value, the minimum relative error was 0.096% and the maximum error was 6.960%. The results show that response surface methodology can be used to optimize the mix ratio of composite modified asphalt mixtures. [7]

Patricia Peña-Pichardo, Gonzalo Martínez-Barrera, Miguel Martínez-López, Fernando Ureña-Núñez and João Marciano Laredo dos Reis (2018) had study Recovery of Cotton Fibers from Waste Blue-Jeans and its use in Polyester Concrete. In this work, polyester concrete with waste cotton fibers was elaborated, and a novel treatment by gamma irradiation was carried out. The results show up to 40% improvement on the compressive strength, as well as 7% on the flexural strength. Modifications on the surface, chemical structural and crystallinity of irradiated waste cotton fibers, were related with improvements on the mechanical properties of concrete. [8]

Babak Mirbaha, Ali Abdi Kordani, Mohammad Zarei and Ali Zarei (2017) had study Experimental Determination of the Optimum Percentage of Asphalt Mixtures Reinforced with Nano-Carbon Black and Polyester Fiber Industries. In this research, by adding different percent amounts of black nano-carbon and polyester fibers as modifier in the asphalt mixtures and conducting several Marshall tests, it was observed that adding these two additives can improve generally the Marshall results. According to the results, Marshall stability is increased up to 61%. Furthermore, an economic analysis was performed to investigate the cost of using such modified asphalt mixtures for constructing 1 km of a six-line road and suitable percentages of additives were found from mechanical-economic analyses. [9]

## 3. Methodology

3.1 The sample in the experiment

Fibers in the experiment were polypropylene-polyethylene terephthalate; PP-PET, used in the manufacturing process of a nonwoven fabric manufacturer in Thailand. There were 4 sets of the sample. Details of variables studied were mentioned in the next topic.

3.2 The Variables studied in the experiment.

Variables in the study consisted of independent variable, i.e., the ratios between polyester fabric scraps from the manufacturing process and 100% polyester fabric, 4 ratios, and dependent variable, i.e., properties of nonwoven fabrics compliant to standards. Consideration was given to weight, tensile, elongation, and thickness of fibers. Details are shown in Table 2.

**Table 2** shows independent variable and dependent variable of the experiments for the 4 ratios.

| Ratios | Independent Variable | | Dependent Variable | |
|---|---|---|---|---|
| | Polyester Scraps | 100% Polyester | Properties | Accepted criteria * |
| Ratio 1 | 4 | 96 | Weight (g) | 25 - 29 |
| Ratio 2 | 6 | 94 | Tensile Strength (nm.) | 22.00-26.00 |
| Ratio 3 | 8 | 92 | Elongation (nm.) | 4.00-6.00 |
| Ratio 4 | 10 | 90 | Thickness (mm.) | 0.9 - 1.4 |

*Accepted criteria of physical test according to Thai Industrial Standard Test Methods for Textiles Number 121, part 12, 16, 17 and 24, respectively. [10-14]

3.3 The place where the experiments were performed, inspectors, and raw materials in the experiments.

Raw materials in the experiments were polyester fabric scraps left over from the manufacturing process mixed with 100% polyester fabrics for nonwoven fabric with 100 millimeters width and 3,000 meters length.

3.4 Steps of the implementation and experiments. There were 2 parts as follows:

3.4.1 Study problems and information about waste in nonwoven fabric manufacturing process consisting of the following sub-steps:

3.4.1.1 team meeting to summarize problems about polyester fabric scraps left over from the nonwoven fabric manufacturing process.

3.4.1.2 analyze arising problems using fish bone diagram to identify the root of polyester fabric scraps left over from the nonwoven fabric manufacturing process and seek a guideline to improve the nonwoven fabric manufacturing process.

3.4.2 Experimental step consists of the following sub-steps:

3.4.2.1 Prepare polyester scraps left over from the manufacturing process and 100% polyester fabric according to the ratio: 4:96, 6:94, 8:92 and 10:90.

3.4.2.2 Prepare a machine used in the experiment, i.e., re-fiber machine. The machine was inspected and set to be ready for use as required by standards.

3.4.2.3 Prepare an instrument for recording information during the experiment is performed, i.e., check sheet to record product properties.

3.4.2.4 Bring polyester fabric scraps left over from the manufacturing process and 100% polyester fabric to put in the re-fiber machine to mix the fibers. Next, newly mixed nonwoven fibers from 4 ratios are obtained among 120 samples (30 samples per ratio).

3.4.2.5 All 120 nonwoven fabric samples are inspected and recorded results. QC inspectors conduct an inspection thoroughly according to the sub-steps as follow:

1) Inspect weight by cutting 2x2 millimeters nonwoven fabric sample and inspecting from the right side, at the middle and the left side.
2) Inspect tensile by cutting 2x2 millimeter nonwoven fabric sample and inspecting from the right side, at the middle, and the left side.
3) Inspect elongation by cutting 2x2 millimeter nonwoven fabric sample and inspecting from the right side, at the middle, and the left side.
4) Inspect thickness by cutting 2x2 millimeter nonwoven fabric sample and inspecting from the right side, at the middle, and the left side.
5) Analyze primary data – the data recorded from the inspection are
6) measured mean to compare standard properties and accepted criteria of physical test based on Thai Industrial Standard Test Methods for Textiles Number 121, part 12 – weight, part 16 – tensile, part 17 – elongation, and part 24 – thickness.
7) Analyze in-depth data to seek the optimal mixing ratio between polyester fabric scraps left over from the manufacturing process and 100% polyester fabric.
8) Make a conclusion and discussion about experimental results.

3.5 Principles of statistics and instruments used for experimental result analysis

3.5.1 Mean was used to analyze 30 experimental data sets to compare weight, tensile, elongation and thickness properties according to Thai Industrial Standard Test Methods for Textiles Number 121.

3.5.2 Actual process capability index (Cpk) [15-16] consists of the following calculation formulas:

$$Cpu = (USL - Average) / (3\sigma) \quad (1)$$

$$Cpl = (Average - LSL) / (3\sigma) \quad (2)$$

$$Cpk = \min \text{ of } \{Cpu \text{ and } Cpl\} \quad (3)$$

by considering

If Cpk < 1.0, it is considered the process is not capable of meeting its requirements.

If Cpk = 1.0, it means the process is barely capable.

If Cpk > 1 or greater than 1.33, it means the process is capable or has natural variation. [17]

3.5.3 Minitab is a software package used for data analysis and statistical processing including presentation of process capability report.

## 4. Results

According to the experiments to find out the optimal mixing ratio between polyester scraps left over from the manufacturing process and 100% polyester fabric based on the 4 ratios. The study result analysis is divided into 3 parts as:

4.1 Analysis results of the means of the 30 experimental data sets are shown in Table 3

**Table 3** The mean of the ratio 4:96, 6:94, 8:92 and 10:90 compared to Thai Industrial Standard Test Methods for Textiles Number 121. Properties

| Properties | Mean (n=30) | | | | Criteria | Results |
|---|---|---|---|---|---|---|
| | 1st Ratio (4:96) | 2nd Ratio (6:94) | 3rd Ratio (8:92) | 4th Ratio (10:90) | | |
| Weight | 27.5 | 27.9 | 28.20 | 29.00 | 25 - 29 | Pass |
| Tensile Strength | 25.85 | 24.41 | 21.89 | 21.64 | 22 - 26 | Pass |
| Elongation | 5.05 | 4.40 | 3.61 | 3.65 | 4 - 6 | Pass |
| Thickness | 1.07 | 1.10 | 1.37 | 1.33 | 0.9 - 1.4 | Pass |

From Table 3 the analysis results of the means of the 30 experimental data sets found there were 2 ratios that passed the criteria and 2 ratios that did not pass the criteria. The accepted ratios, the 1st ratio and the 2nd ratio were analyzed process capability accordingly.

4.2 Analysis results of process capability – after the mean of the 1st ratio (4:96) and the mean of the 2nd ratio (6:94) were analyzed, short term process capability analysis was performed using actual process capability index (Cpk) to find out the process capability that shall meet the requirements of the product standards to ensure the experimental results are more precise.

4.2.1 Analysis results of process capability using Cpk value for the 1st ratio (4:96) according to the standard requirements of nonwoven fabrics are shown in the following figures:

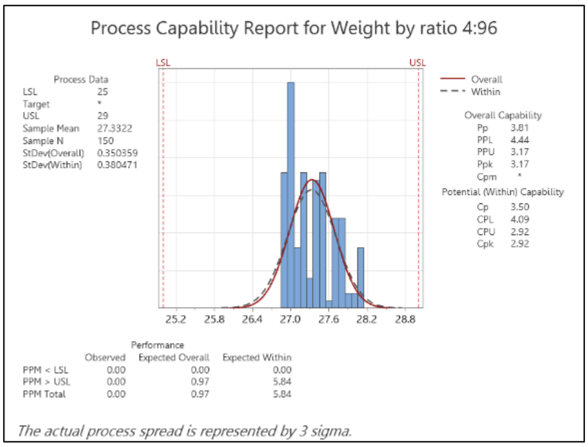



**Figure 1** shows Cpk value for the 1st ratio 4:96 according to weight property of nonwoven

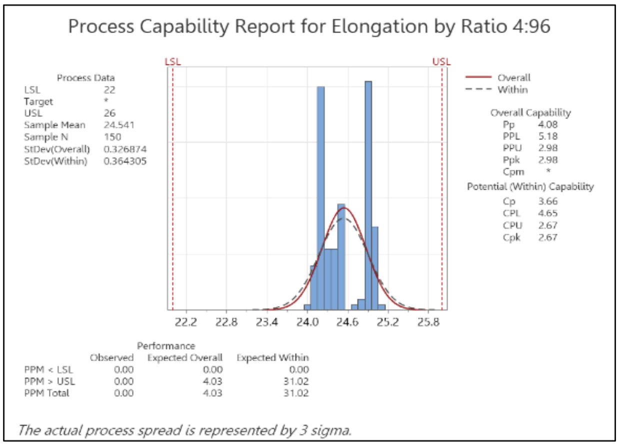



**Figure 2** shows $C_{pk}$ value for the 1st ratio 4:96 according to Tensile Strength property of nonwoven fabrics.

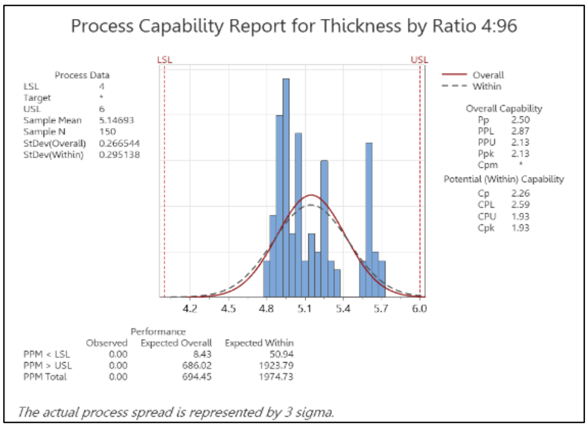



**Figure 3** shows Cpk value for the 1st ratio 4:96 according to Elongation property of nonwoven

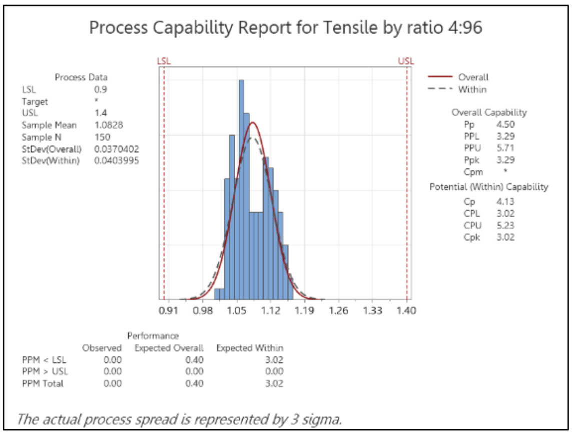



**Figure 4** shows Cpk value for the 1st ratio 4:96 according to Thickness property of nonwoven fabrics.

Figures 1-4 show the nonwoven fabric process having the mixing ratio between polyester scraps left over from the manufacturing process and 100% polyester fabric at the ratio of 4:96. Total average Cpk value from 5 times experiments based on 30 experimental data sets found the weight was 2.92, tensile was 2.67, elongation was 1.93, and thickness was 3.02. It can be described that if Cpk > 1 or greater than 1.33, [16] the process is capable or has natural variation. Considered the average variation, the process is at the center of the requirement standards, meaning the manufacturing process meets manufacturing standards.

4.2.2 Analysis results of process capability using Cpk value for the 2nd ratio 6:94 according to the standard requirements of nonwoven fabrics are shown in the following figures:

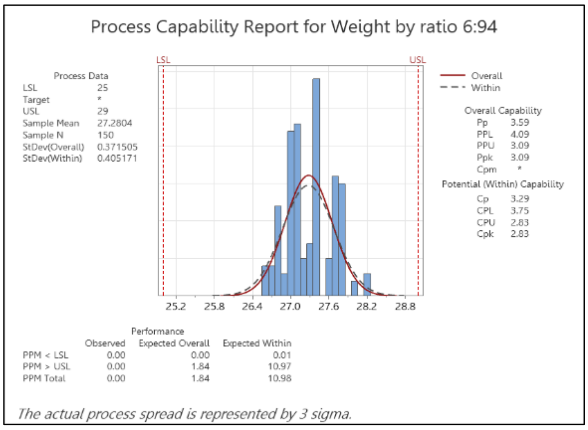



**Figure 5** shows Cpk value for the 2st ratio (6:94) according to weight property of nonwoven fabrics

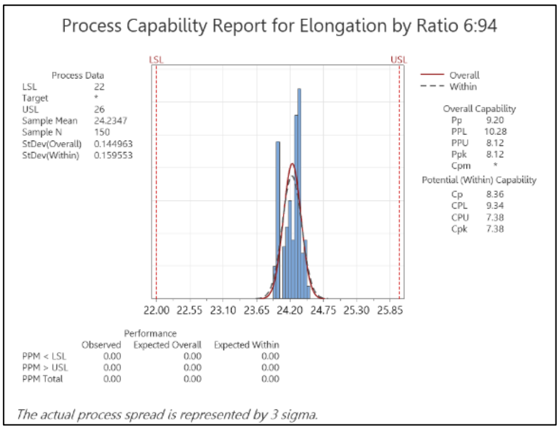



**Figure 6** shows Cpk value for the 2st ratio (6:94) according to Tensile Strength property of nonwoven fabrics.

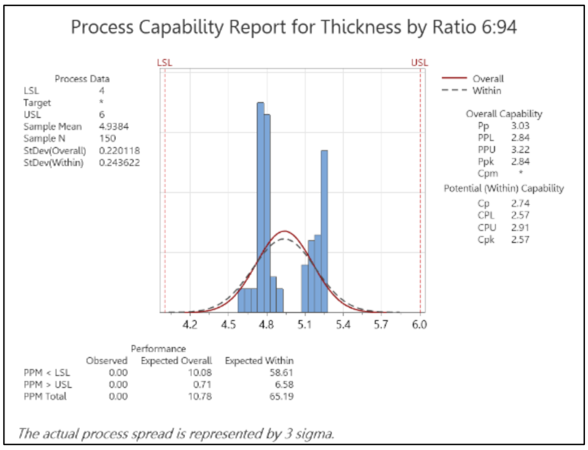



**Figure 7** shows Cpk value for the 2st ratio 6:94 according to Elongation property of nonwoven fabrics.

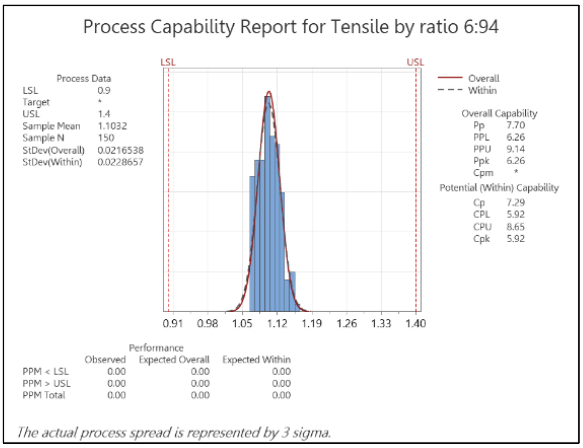



**Figure 8** shows Cpk value for the 2st ratio 6:94 according to Thickness property of nonwoven fabrics.

Figures 5-8 show the nonwoven fabric process having the mixing ratio between polyester fiber scraps left over from the manufacturing process and 100% polyester fabric at the ratio of 6:94. Total average Cpk value from 5 times experiments based on 30 experimental data sets found the weigh was 2.83, tensile was 7.38, elongation was 2.57, and thickness was 3.02. It can be described that if Cpk > 1 or greater than 1.33, the process is capable or has natural variation. Considered the average variation, the process is at the center of the requirement standards, meaning the manufacturing process meets manufacturing standards.

4.3 Experimental results and the optimal mixing ration between polyester fiber scraps left over from the manufacturing process and 100% polyester fabric, based on data collection after the improvement according to the 1st ratio and the 2nd ratio are shown in Figure 9.

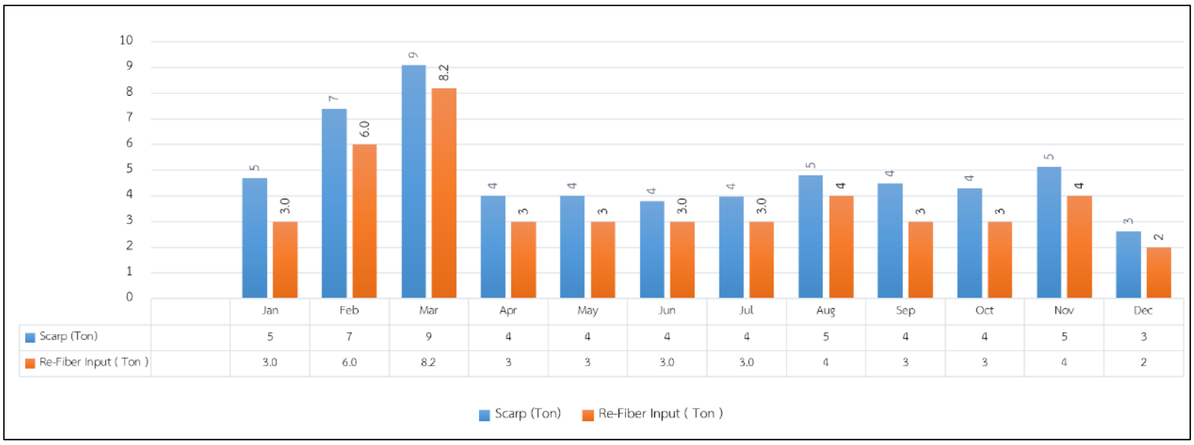
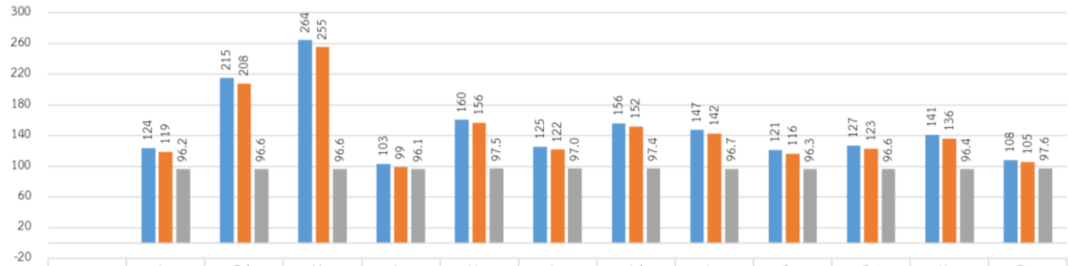



**Figure 9** shows the quantity of polyester fiber scraps left over from the manufacturing process and the quantity that can be reused.

From Figure 9, after the manufacturing process was improved and the data in the period of 12 months were studied, it was found that there were 58 tons of polyester fiber scraps left over from the manufacturing process and 45 tons were reused or accounted for 77.58% of the polyester fiber scraps left over from the manufacturing process. Efficiency of the manufacturing process measured by yield (%) is shown in Figure 10.




| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fiber input (Ton) | 124 | 215 | 264 | 103 | 160 | 125 | 156 | 147 | 121 | 127 | 141 | 108 |
| Finised Goods (Ton) | 119 | 208 | 255 | 99 | 156 | 122 | 152 | 142 | 116 | 123 | 136 | 105 |
| Yield ( %) | 96.2 | 96.6 | 96.6 | 96.1 | 97.5 | 97.0 | 97.4 | 96.7 | 96.3 | 96.6 | 96.4 | 97.6 |

Fiber input (Ton) Finised Goods (Ton) Yield ( %)

**Figure 10** shows efficiency of the manufacturing process measured by yield (%) in the period of 12 months.

From Figure 10, after the nonwoven fabric manufacturing process was improved, showing efficiency of the manufacturing process measured by yield (%) in the period of 12 months, there were 1,792 tons of 100%

## 5. Conclusion and Discussion

The research aimed to study the optimal mixing ratio between polyester fabric scraps left over from the manufacturing process and 100% polyester fabrics. Independent variable was the ratio between polyester fabric scraps left over from the manufacturing process and 100% polyester fabrics. Dependent variable was properties of nonwoven fabric according to Thai Industrial Standard Test Methods for Textiles Number 121 (parts 12, 16, 17 and 24). In the test, there were 4 sets of ratios, i.e. 4:96, 6:94, 8:92 and 10:90). Conclusion and discussion of experimental results are shown below:

5.1 Conclusion

According to the analysis results of the means, the optimal ratio between polyester fabric scraps left over from the manufacturing process and 100% polyester fabric, 4:96, had the total average weight equal to 27.5 grams per square meter, thickness equal to 1.07 millimeters, tensile equal to 25.85 newton meters, and polyester fabrics and 1,733.70 tons were used in the manufacturing process or the yield of 96.7% of the manufacturing process efficiency. Therefore, the manufacturing process was accepted after improvement had been made elongation equal to 5.05 newton meters, meeting the requirements in every test result.

According to the analysis results of the means, the optimal ratio between polyester fabric scraps left over from the manufacturing process and 100% polyester fabric, 6:94, had the total average weight equal to 27.9 grams per square meter, thickness equal to 1.10 millimeters, tensile equal to 24.41 newton meters, and elongation equal to 4.40 newton meters, meeting the requirements in every test result.

According to the analysis results of the means, the optimal ratio between polyester fabric scraps left over from the manufacturing process and 100% polyester fabric, 8:92, had the total average weight equal to 28.20 grams per square meter, thickness equal to 1.37 millimeters, meeting the requirements, but tensile equal to 21.89 newton meters and elongation equal to 3.61 millimeters, did not meet the requirements. Therefore, the 8:92 ratio was not suitable due to decreased tensile and elongation.

According to the analysis results of the means, the optimal ratio between polyester fabric scraps left over from the manufacturing process and 100% polyester fabric, 10:90, had the total average weight equal to 29.21 grams per square meter, thickness equal to 1.33 millimeters, tensile equal to 21.64 newton meters and elongation equal to 3.65 millimeters, which did not meet the requirements, except for the weight. Therefore, the 10:90 ratio was not suitable due to decreased thickness, tensile and elongation.

The analysis results of process capability after the analysis results of the means of the 1st ratio (4:96) showed total average Cpk value of the weight equal to 2.92, tensile equal to 2.67, elongation equal to 1.93 and thickness equal to 3.02. The 2nd ratio (6:94) showed total average Cpk value of the weight equal to 2.83, tensile equal to 7.38, elongation equal to 2.57 and thickness equal to 3.02, indicating that the process was capable or had natural variation.

5.2 Discussion

According to the study on the optimal mixing ration between polyester fabric scraps and 100% polyester fabric: a case study of nonwoven fabric manufacturer in Rayong province, Thailand, weight, thickness, tensile and elongation properties were tested in accordance with Thai Industrial Standard Test Methods for Textiles Number 121 (parts 12, 16, 17 and 24), Thailand Textile Institute. There is consistency with test methods in a study conducted by Pongsaroge Nimmannorraluk, Pairust Vongyuttakrai and Thanarat Tavattana (2013) on A Study on Waste Reduction Through Machine Adjustment and Ratio Formulation in Nonwoven Fabric Material Production, which the same standards were used. The experimental results based on the 4:96 ratio and 6:94 ratio revealed the properties consistent with the manufacturing process standards but the 8:92 ratio indicated that tensile and elongation properties were not compliant with the manufacturing process standards. The 10:92 ratio revealed weight, tensile, and elongation properties were not compliant with the manufacturing process standards. [3] This is consistent with a study conducted by Jaroenyot R., Anuntaratanachai S., Sujittamakul P. (2015) to study of the qualification of polymer mixed glass fiber for the material of the windwheel produced the electric current. The test pieces were made in 70:30, 60:40 and 50:50 ratio respectively and those were tested for tensile strength, flexural strength, hardness and attrition resistance. Results indicated that glass fiber-reinforced polyester wrapped with ceramic fiber-reinforced epoxy at 70:30 compositions contained the best mechanical properties. [18]

## 6. Acknowledgement

This research was successful with the cooperation and support from a lot of persons.

The researcher would like to extend gratitude to Asst. Prof. Dr. Sudasawan Ngammongkolwong, Dean of Faculty of Digital Technology and Innovation, Southeast Bangkok University who gave good advice and support in every step for conducting the research.

The researcher would to express thankfulness to Dr. Sojiluk Kamonsakdavikul, Director of Research and Academic Services Office, Southeast Bangkok University who gave good advice and how to conduct research documents.

The researcher would like to thank the case study company for the warm welcome and permission to the researcher to visit the company as the data source of this research as well as support given until the research was completely successful.

The researcher would like to thank the secretary and officers of Faculty of Digital Technology and Innovation, Southeast Bangkok University for the communication, coordination, and facilities provided.

Lastly, the researcher would like to thank Southeast Bangkok University for the support and research funding.

## References

[1] Department of Industrial Works Ministry of Industry, Industrial Data and Digital Center, *"Number of workers in textile and garment factories (accumulation),"* [Online]. Available: https://www.thaitextile.org/th/insign/detail.1574.1.0.html. [Accessed: June 25, 2022].

[2] Textile Industry Development Institute, Situation of Thai Textile and Garment Industry, Industrial Data and Digital Center. *"Textile Industry Development Institute: 2020,"* [Online]. Available: https://www.thaitextile.org/th/insign/detail.2000.11.0.html. [Accessed: June 25, 2022].

[3] P. Nimmanorraluk, P. Vongyuttakrai, T. Tavattana. "A Study on Waste Reduction Through Machine Adjustment and Ratio Formulation in Nonwoven Fabric Material Production," *Journal of Industrial Studies*, vol.7, no.2, pp. 33-41, 2013.

[4] S. Saikaew, S. Wiengwiset, A. Sriboonruang. "Improving the Properties of Sand Molds in the Iron Casting Industry Using Mixture Experiments," *KKU Research Journal,* Vol. 16, No.2, pp. 169-78, 2011.

[5] S. Kaewploy, K. Boonseng. "Design of Experiment for Evaluating the Optimal Condition in Drying Process of Rubberwood," *KKU Research Journal,* vol.19, no.2, pp. 84-92, 2014.

[6] S.R. Nadupuru, R.K. Jain, D.A. Joshi and R. Menon. "Experimental Analysis using Polypropylene, Polyester and Waste Denim Fiber in Road Construction," *International Conference on Recent Advances in Engineering Materials*, vol.66, no.4, pp. 2363-2369, 2022.

[7] Y. Gong, J. Song, H. Bi and Z. Tian. "Optimization Design of the Mix Ratio of a Nano-TiO2/CaCO3-Basalt Fiber Composite Modified Asphalt Mixture Based on Response Surface Methodology," *Journal: Applied Sciences*, vol.10, no13, pp.1-24, July 2020.

[8] P.P. Pichardo, G.M. Barrera, M.M. López, F.U. Núñez and J.M. Laredo. "Recovery of Cotton Fibers from Waste Blue-Jeans and its use in Polyester Concrete," *Construction and Building Materials*, vol.177, pp.409-416, 20 July 2018.

[9] B. Mirbaha, A.A. Kordani, M. Zarei and A. Zarei. "Experimental Determination of the Optimum Percentage of Asphalt Mixtures Reinforced with Nano-Carbon Black and Polyester Fiber Industries," *Engineering Solid Mechanics*, vol. 5, no.4, 2017, pp. 285-292, 2017.

[10] Thai Industrial Standards Institute. Office Industrial Product Standards, Ministry of Industry. *"Standard Document Industry 121:1979,"* [Online]. Available: https://www.tisi.go.th/website/standardlist/list_measures. [Accessed: June 25, 2022].

[11] Thai Industrial Standards Institute. Office Industrial Product Standards, Ministry of Industry. *"Industrial product standards Woven Fabrics-Determination of Mass per Unit Length and Mass per Unit Area TIS.121 Volume 12:2010,"* [Online]. Available: http://www.fio.co.th/web/tisi_fio/fulltext/TIS121_12-2553.pdf. [Accessed: June 25, 2022].

[12] Thai Industrial Standards Institute. Office Industrial Product Standards, Ministry of Industry. *"Industrial product standards Tensile Properties of Fabrics -Determination of Maximum Force Using the Grab Method TIS.121 Volume 16:2010,"* [Online]. Available: http://www.fio.co.th/web/tisi_fio/fulltext/TIS121_16-2553.pdf. [Accessed: June 25, 2022].

[13] Thai Industrial Standards Institute. Office Industrial Product Standards, Ministry of Industry. *"Industrial product standards Determination of Tear of Fabrics Using Constant Rate of Extension Testing Machine TIS.121 Volume 17:2010,"* [Online]. Available: http://www.fio.co.th/web/tisi_fio/fulltext/TIS121_17-2553.pdf. [Accessed: June 25, 2022].

[14] Thai Industrial Standards Institute. Office Industrial Product Standards, Ministry of Industry. *"Industrial product standards Thickness of Fabrics TIS.121 Volume 24:2010,"* [Online]. Available: http://www.fio.co.th/web/tisi_fio/fulltext/TIS121_24-2553.pdf. [Accessed: June 25, 2022].

[15] D.C. Montgomery, *Introduction to Statistical Quality Control,* John Wiley & Sons Inc, New York, 2005.

[16] B. Ramakrishnan, P.M. Sandborn Pecht, *Process Capability Indices and Product Reliability,* Microelectronics Reliability. 2001.

[17] J. Sabseree, Quality Production, Technology Promotion Association (Thailand-Japan): 2007. *"Process Capability Analysis,"* [Online]. Available: https://www.tpa.or.th/publisher/pdfFileDownloadS/fq121_p56-59.pdf. [Accessed: Dec. 5, 2022].

[18] R. Jaroenyot, S. Anuntaratanachai, P. Sujittamakul., Rajamangala University of Technology Suvarnabhumi: 2015. *"The Study of the Qualification of Polymer Mixed Glass Fiber for the Material of the Windwheel Produced the Electric Current"* [Online]. Available: https://research.rmutsb.ac.th/fullpaper/2558/2558240240238.pdf. [Accessed: Dec. 18, 2022].