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Comparison of Stain Removal Characteristics of Knitted Structures

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ABSTRACT

The subject of stains and stain removal has great importance to the professional lives of textile researchers and the daily lives of the public. Therefore, stain removal characteristics of five different types of 100% cotton knitted fabrics (single-jersey, piquet, 3-thread fleece, 1x1 rib, and interlock) commonly used for casual wear were investigated in this study. Samples were stained with three types of common stains, and the effects of various fabric properties on stain removal characteristics were investigated. The stain removal performance was evaluated both objectively via a spectrophotometer and subjectively by Grey Scale grading. According to the results, fabric structure had a significant effect on stain removal characteristics. 1x1 rib and single jersey were the most difficult structures for stain removal, whereas, piquet fabric was the most convenient. Additionally, tomato paste was the most difficult stain to remove, whereas chocolate milk was the easiest.

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Stain, stain removal, knitted fabric, fabric structure, spectrophotometer

1. INTRODUCTION

Staining and stain removal of fabrics by laundering are important issues in both daily life and textile literature. Laundering is a process in which physical and chemical effects interact in the washing water. The first phase of laundering is the removal of soil from the fabric, the second phase is stabilizing the soil to prevent redeposition onto the fabric and the last phase is removing dirt and chemicals from the laundry with the help of rinsing process [1]. A successful soil removal by washing depends largely on factors such as fabric type, the type of soil, wash load, type of washing machine, water quality, applied washing conditions (amount and type of mechanical action, time, and temperature), and the composition of the detergent [2-4]. Efficient cleaning is only possible when certain factors such as chemical action, mechanical action, temperature, and time come together [1]. Researchers in the field of textiles have long been studying the removal of stains from the surface of textiles left by the soils and the effects of various washing conditions on stain removal.

Bueno et al. [5] studied the modeling of the kinetics of stain removal from cotton-knitted fabrics using a commercial washing machine. They focused on the physical process of stain removal by varying the textile load, washing time, and drum rotational speed. A new mathematical model was suggested to explain the effect of mechanical action present during the washing process and the extent of stain removal. Fen-Juan et al. [6] investigated the usage of image analysis in determining the degree of stain removal. In that study, standard stain cloths were washed under various washing conditions, and washing efficiency was analyzed. Additionally, the stain photos taken before and after washing were compared via image analysis. As a result, it was concluded that the results of washing efficiency and image analysis were significantly correlated, and image analysis could be used to evaluate stain removal.

In the literature review, it is seen that there are various studies on stain resistance. Kabbari et al. [7] studied predicting the stain-repellency characteristics of plush knitted fabrics by comparing surface response and fuzzy logic methods. It was observed that the fuzzy logic model

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had a better prediction performance, and it could be applied in the knitting industry. Chauhan et al. [8] evaluated the mechanical, chemical, thermal, and UV stability of the superhydrophobic cotton fabric. They developed a modified cotton fabric with self-cleaning and stain-resistant properties with a proposed method. Pallye and Ghosh [9] developed a super-hydrophobic and stain-repellent fabric finish. Additionally, a stain-repellent fabric for use in aircraft upholstery was designed by Kuruppu [10].

Moreover, forensic scientists are interested in staining characteristics of various fabrics, as well. Because apparel with bloodstains is important evidence, bloodstain pattern analysis (BPA) has become a popular research topic in the field of forensic science [11]. Miles et al. [12] investigated fabric surface characteristics for satellite bloodstain morphology using a pair of denim jeans (98/2% cotton/elastane) and a t-shirt (95/5% cotton/elastane) selected for staining. It was concluded that surface roughness influences the morphology of stains generated and the increasing of surface roughness leads to an increase in the number and extent of satellite stains. Dicken et al. [13] stated that factors of bloodstain size for non-absorbent surfaces are still being investigated, however, interactions between blood and fabrics are still quite unknown. Therefore, they used a micro-computed tomography (CT) scanner to examine the bloodstain size and shape on the surfaces of the 100% cotton rib knit and 100% cotton drill woven fabrics. It was observed that the bloodstain morphology depended on both the impact velocity and fabric structure. De Castro et al. [11] examined the effect of various factors affecting appearances, such as prior laundering, fiber content, fabric structure, and blood impact angle on drip bloodstain appearance. They used four different fabrics that are 100% cotton plain woven, 100% polyester plain woven, a blend of polyester and cotton plain woven, and 100% cotton single jersey knit fabrics. It was observed that the bloodstain characteristics change according to fiber content and fabric structure and these factors should be taken into consideration while interpreting bloodstain patterns. Williams et al. [14] researched the impact dynamics of porcine drip bloodstains on fabrics. The number and size of satellite stains were examined on two types of 100% cotton fabrics (a plain woven bed sheet and a jersey knit). A correlation was observed between surface roughness and some satellite bloodstains. A higher number of satellite stains occurred on more rough surfaces. Furthermore, Nolan et al. [15] thought that in some criminal cases victims' clothes may have been washed several times before a criminal investigation. Therefore, they investigated the effects of repeated washing process and fabric type on the permanence of seminal fluid and spermatozoa using various fabrics (cotton, nylon, cotton terry towel, polyester fleece, satin, and lace) laundered up to six times. However, it was concluded that further research should be conducted to distinguish the effects of fabric construction.

Despite significant results concluded by forensic researchers, comparing two quite different fabric types, (knitted and woven fabrics), may not be sufficient from a textile point of view. Because many characteristics such as fabric production method (knitted, woven, or nonwoven), the structure of knitted fabric (single jersey, rib, interlock, etc.) and woven fabric (plain, twill, satin, etc.), and the yarn material have important effects on staining behavior of the fabrics. To overcome this lack, collaborations between forensic and textile researchers were formed. Li et al. [16] examined the effect of yarn production methods on wicking and bloodstain pattern analysis (BPA) on woven cotton fabrics. They observed that fabrics made with ring-spun yarns wicked more blood than open-end and vortex yarns. In another study, Baby et al. [17] investigated the effects of yarn count and blood drop size on wicking and bloodstains on textiles. It was concluded that samples knitted with finer yarns had larger stains. Wu et al. [18] dropped the blood on three 100% cotton single jersey knit fabrics with different yarn counts and also onto paper. Results showed that number and area of the stains decreased, as the yarn count decreased.

Although staining and stain removal characteristics of fabrics are significant subjects in both academic and daily life, it is observed that the influence of fabric structure, a main characteristic of fabrics, on stain removal is not investigated in detail. Therefore, in this study, the stain removal characteristics of five different knitted fabrics frequently used in casual garments were examined. To simulate some common stains, three different types of stains were used (tomato paste, red wine, and chocolate milk).

2. MATERIAL AND METHOD

2.1 Material

To include knitted structures that are frequently used in daily life in the scope of the experiment, five knitted fabrics knitted in different structures using 100% cotton ring yarn were supplied by a textile company. To create a wide range of fabrics, structures produced on both single-bed and double-bed circular knitting machines were included in the research. While three fabric structures (single-jersey, piquet, and 3-thread fleece) were knitted on a single-bed circular knitting machine, others (1x1 rib and interlock) were produced on a double-bed circular knitting machine.

2.2 Method

As the aim of this study is to investigate the effect of fabric structure on the stain removal property, some fabric characteristics that were expected to influence the porosity were measured besides fundamental fabric properties. Because Bueno et al. [5] stated that stain removal of textiles depends on two main porosities of fabrics. The first and larger porosity are the spaces between the yarns (inter-yarn), and the second and smaller porosity are the spaces between fibers within the yarns (intra-yarn).

The measured properties were mass per unit area, courses per cm, wales per cm, fabric thickness, air permeability, and hydrophility. Mass per unit area, courses per cm, and wales per cm determine the amount of yarn in the unit area. Fabric thickness is a significant parameter for successful stain removal as it defines the distance that washing liquor should travel between the front and the back sides of the fabric. These values collectively affect the fabric density and fabric tightness, thus, fabric porosity. Air permeability value is known to be directly related to fabric porosity. The coefficient of friction identifies the surface roughness of the fabric. A smoother surface provides a larger contact area for the washing liquor resulting in a more effective stain removal than a rougher surface. In addition, the hydrophility of the samples affects the wicking of the soils. Moreover, *L (luminance)* values of the clean fabrics (before staining and washing) are measured to observe if the luminance of the samples affects stain removal performance. Since generally preferred fabrics in casual garments were chosen as the test samples in this study, some other properties are quite different from each other, except for the fiber content used. Therefore, the fabric density value was used to compare the fabrics with each other. The fabric density is the weight per unit volume of the fabric that allows for determining how strong, dense, and permeable the fabric is. Therefore, this parameter was calculated to evaluate some properties of the samples using Equation (1):

$$FD=m_s/t \quad (1)$$

where: FD – fabric density, [g/cm^3]; m_s – mass per unit area of the fabrics [g/m^2]; t – fabric thickness [mm]. The used symbols, units, related test standards, used test devices, and repetitions of tests for each parameter during tests are listed in Table 1.

All samples were conditioned before measurements and the tests were conducted in standard atmosphere conditions. Stitch diagrams and measured properties of five different fabric structures are given in Table 2.

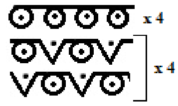
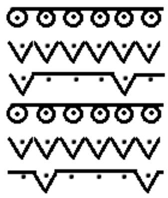
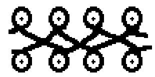
As per the International Association for Soaps, Detergents and Maintenance Products (A.I.S.E.), soil types are classified as bleachable, enzymatic, particulate, and greasy. Bleachable and enzymatic soils are predominantly preferred for laundry detergent performance tests [19]. They are quite common in consumer habits and are usually easier to remove without a pre-treatment. Therefore, chocolate milk (enzymatic), red wine (bleachable), and tomato paste (bleachable) were selected for this study. Because of the denser character of tomato paste, 15 g of tomato paste was diluted with 50 ml of water to obtain a homogeneously applicable soil. Each type of soil was poured into a clean bowl. Soils were applied to the fabrics via a brush and a circular templet with a 5 cm diameter (Figure 1) in standard atmosphere conditions.

Figure 1. Circular templet used for soiling

Table 1. Tested parameters and related test standards

Parameter	Symbol	Unit	Related standard	Test device	Repetition
Mass per unit area	m_s	g/m^2	TS EN 12127:1999	Digital scale with .000 accuracy	3 times
Course per cm	cpc	-	TS EN 14971: 2006	Magnifying glass	3 times
Wale per cm	wpc	-	TS EN 14971: 2006	Magnifying glass	3 times
Thickness	t	mm	TS 3374 ISO 1765: 2004	Wira Digital Thickness Gauge (2 kPa presser foot)	3 times
Fabric density	FD	g/cm^3	-	Calculated	-
Coefficient of friction	μ_k	-	-	Frictorq	3 times
Air permeability	AP	l/m^{2}s	ISO 9237:1995	Textest FX 3300 (pressure difference of 100 Pa and sample area of 20 cm^2)	10 times
Hydrophility	H	s	AATCC 79:2007	Burette	5 times
Luminance	L	-	ASTM E1331	HunterLab UltraScan PRO spectrophotometer	4 times
Color difference	*ΔR*	-	ASTM E1331	HunterLab UltraScan PRO spectrophotometer	4 times

Table 2. Stitch diagrams and measured properties of samples

Fabric structure	Yarn count	m_s	cpc	wpc	t	FD	µk	AP	L	H	Stitch diagram
	Ne	g/m^2	course /cm	wale/ cm	mm	g/cm^3		l/m^2s	-	s	
Single jersey	35	220	19	15	0.70 a	0.31	0.2948 a	187 a	93.47	12	
Piquet	30	180	16	13	0.78 b	0.23	0.3494 b	540 b	96.20	14	
Fleece (Three thread)	50/50/ 20	200	18	12	1.17 c	0.17	0.3681 c	652 c	93.69	4	
1x1 Rib	30	200	16	11	0.89 B	0.22	0.3048 A	393 B	87.79	60+	
Interlock	40	200	17	16	0.83 A	0.24	0.3085 A	319 A	96.48	3	

Four samples were created for each kind of stain for repetition. After 24 hours, stained parts of the samples were folded in four layers, and measurements were taken in a wale direction with a HunterLab UltraScan PRO spectrophotometer. The reflectance values of the samples were recorded at 460 nm wavelength.

Then, samples were laundered in a Type A washing machine according to ISO 6330: 2012 (E) (Procedure No. 4N, normal washing) with 20 g of Reference detergent 2. Washed samples were laid on a flat surface to dry for 24 hours. Afterward, spectrophotometer measurements were repeated in the same way. From the reflectance values measured before and after washing, the color differences (ΔR) were calculated as shown in Equation (2) [20]. As it is known, higher ΔR means better stain removal.

$$\Delta R = RA - RB \quad (2)$$

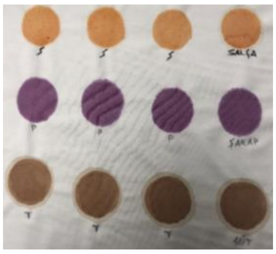
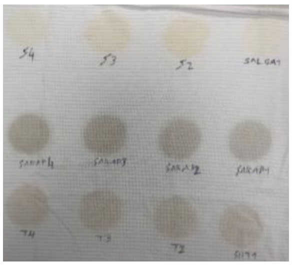
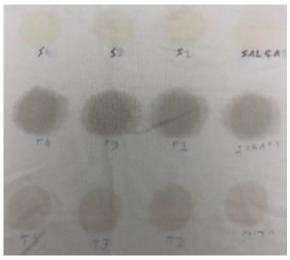
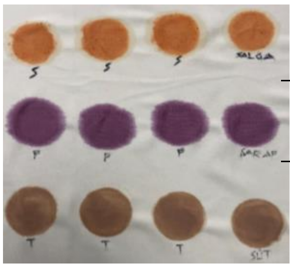
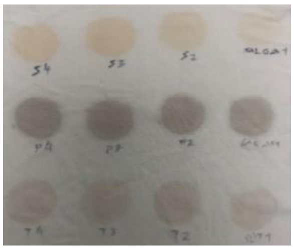
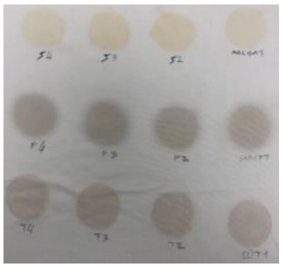
Where; RA: Reflectance value after washing, RB: Reflectance value before washing, and ΔR: Amount of stain removal

Photos of created stains before and after washing are given in Table 3. Stains are lined as tomato paste, red wine, and chocolate milk from top to bottom, respectively.

In addition to the objective evaluation using a spectrophotometer instrument, subjective evaluation was conducted by three experts in this field. AATCC Grey Scale for Staining was used for staining evaluation subjectively. In this scale, the colors of the samples are rated from 1 to 5 (including half steps), where grade 1 means the highest color change while grade 5 means no color change [21].

As known, fabric structures knitted on single-bed and double-bed machines are quite different. Thus, the results of single and double-layer samples were evaluated separately. Test results were evaluated using the software PASW Statistics 18 with a 95% confidence interval. Applied tests to determine the statistical importance of the variations were decided according to the number of fabric structures. The statistical method analysis of variance (ANOVA) and Independent-Samples T Test were applied to single-bed and double-bed samples, respectively. The probability values or p-values were examined to determine whether the parameters were significant or not. If the p-value of a parameter is greater than 0.05 ($p>0.05$), the parameter was accepted as insignificant and was ignored. When the p-value was stated as lower than 0.05 ($p<0.05$), then the Student-Newman-Keuls (S-N-K) posthoc test was used for homogeneous variance and Tamhane's T2 posthoc test was used for heterogeneous variance.

Table 3. Created stains before and after washing

Fabric structure	Before washing	Soil type	After washing
Single jersey		Tomato paste	
		Red wine	
		Chocolate milk	
Piquet		Tomato paste	
		Red wine	
		Chocolate milk	
Fleece (Three thread)		Tomato paste	
		Red wine	
		Chocolate milk	
1x1 Rib		Tomato paste	
		Red wine	
		Chocolate milk	
Interlock		Tomato paste	
		Red wine	
		Chocolate milk	

3. RESULTS AND DISCUSSION

Because Smulders [4] stated that the type of fiber determines the degree of hydrophobicity/hydrophilicity, the wettability, and the extent of soil removal, the fiber type parameter is kept constant. Stain removal results tested by both objective and subjective methods of the samples are given in Table 4. To show the significance level of the difference between mean values in Tables 2 and 4, the measured mean values for each property are marked with letters (from "a" to "c"). The letter “a” shows the lowest value, while the letter “c” presents the highest. Lowercase letters were used for single-layer samples, while uppercase letters were used for double-layer fabrics. Mean values marked with the same letter indicate that they are not significantly different.

As it is known, the $p=0.000$ value means measured values are significantly different from each other in statistical analysis. Therefore, it is possible to say that the coefficient of friction, air permeability, and ΔR values of fabric samples (Figure 2 and Figure 3) for tomato paste, red wine, and chocolate milk stains are significantly different from each other.

Table 4. Stain removal results of the samples

Fabric structure	ΔR			Grey Scale Grading		
	Tomato paste	Red wine	Chocolate milk	Tomato paste	Red wine	Chocolate milk
Single jersey	14.99 a	18.91 a	22.87 a	2	2-3	3
Piquet	30.59 b	38.40 c	35.63 c	3	3-4	4
Fleece (Three thread)	30.64 b	22.24 b	27.31 b	4	2	3
1x1 Rib	14.62 A	18.24 A	23.07 A	1-2	2	3-4
Interlock	26.04 B	42.13 B	34.24 B	2-3	3	2-3

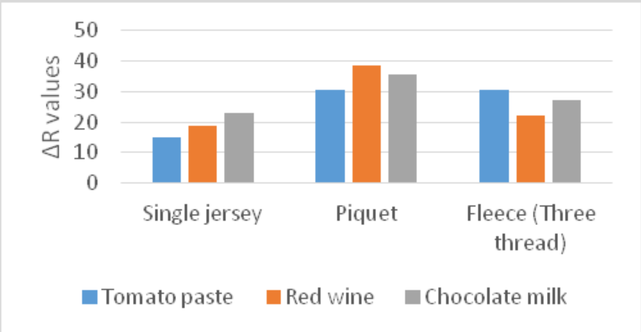


Figure 2. ΔR values of single-layer samples

When the samples produced on a single-bed knitting machine were compared, it was observed that the single jersey fabric had the lowest ΔR value for all stain types. As mentioned before, the lower ΔR value shows that the stain removal capacity from this fabric is poor. This result can be explained by the highest fabric density values of single jersey fabric. As explained in a previous study, the higher fabric density means that the fabric contains more yarn in unit volume [22]. In this case, because of the higher fabric density value, both water and detergent will not be able to reach the stain effectively. Furthermore, as is expected stain is trapped in a dense structure and cleaning can be more difficult for a dense structure than a sparse one. Single jersey structure has the lowest air permeability value among the used fabrics as well. Lower air permeability is related to a lower porosity leading to a less successful stain removal. Additionally, it is seen that Grey scale results obtained from subjective evaluations are compatible with the spectrophotometer results.

Piquet fabric investigated in this study has the best stain removal results of single-layer fabrics. This fabric has lower fabric density and higher air permeability than the single jersey sample because of the tucks between stitches. Because of the lower fabric density both water and detergent reached the stain effectively, and the stain could be easily removed from the fabric structure. Furthermore, a higher air permeability, which is a strong indicator of higher porosity [23], enables the access of both water and detergent. Grey-scale results were similar to the spectrophotometer results of the piquet sample.

Although three-thread fleece fabrics are knitted on the single-bed machine, they have a quite different structure from piquet and single jersey because of comprising three yarns in one course. The three-thread fleece consists of a face yarn, a binding yarn (usually in the same yarn count as the face yarn), and a thicker fleece yarn [24]. This structure has the highest air permeability and the lowest fabric density among the samples knitted on single-bed machines. Yet, a general result can not be reached for its characteristic of stain removal. Because the stain removal level is the same as the piquet structure for tomato paste, on the other hand, the removal level of red wine and chocolate milk stain for three-thread fabric is between the other two structures. As given in Table 4, it is observed that the results of the spectrophotometer and Grey scale are compatible with each other for all kinds of stains on fleece fabric.

Moreover, according to the statistical analysis, the stain removal results strongly depend on the kind of stain for both objective and subjective evaluations, and tomato paste stain is the least removed stain, except for the fleece structure.

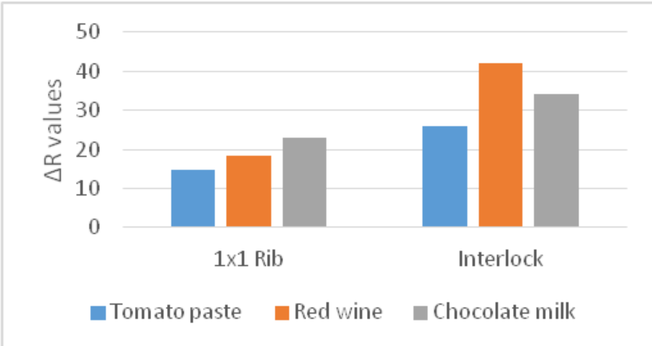


Figure 3. ΔR values of double-layer samples

When double-layer samples are examined, as is expected, it is seen that the 1x1 rib structure has lower fabric density and higher air permeability values. According to the results, 1x1 rib fabric has quite low stain removal results and this means that created stains could not be removed from this fabric structure effectively. 1x1 rib structure consists of one face and one reverse stitched wale, respectively. However, wales with reverse stitches are placed behind the wales with face stitches. That is why reverse wales can only be seen when the fabric is stretched widthwise. Therefore, reverse wales are not fully exposed from both the front and back of the fabric. This may result in a smaller contact area between the fabric and detergent, leading to poor stain removal.

Grey scale gradings and spectrophotometer results of the 1x1 rib sample are mostly aligned.

Although interlock fabric consists of two 1x1 rib fabrics knitted together, it has quite similar values of fabric density and coefficient of friction to 1x1 rib fabric, as seen in Table 2. Yet, ΔR values of interlock are higher than 1x1 rib for all stain types. Spectrophotometer results and Grey scale gradings are mostly compatible for interlock fabric.

When single and double-layer fabrics are considered together, piquet, fleece, and interlock samples have higher ΔR values than single jersey and 1x1 rib fabrics resulting in better stain removal, depending on the type of stain. Regarding red wine and chocolate milk stains, piquet, and interlock samples' ΔR values are significantly higher than fleece fabric. On the other hand, piquet and fleece have better stain removal results in tomato paste stains. Within all five structures, piquet can be regarded as the most convenient fabric structure for stain removal with its higher ΔR and Grey scale results. As per Grey Scale results, chocolate milk stain is considered to be easier to remove than tomato paste and red wine stains. Furthermore, it is observed that ΔR and Grey scale are mainly compatible for the chosen stains.

When the stain removal results and fabric characteristics are evaluated altogether, it can be expressed that among the measured properties fabric density and air permeability are significantly related to a successful stain removal, whereas the coefficient of friction does not have an obvious impact. As it is known, staining and removal of the stain from a fabric surface is rather a complex process and it is affected by various parameters. The cotton fabrics used in the study were provided by a textile company, thus there are discrepancies in some of their structural and mechanical properties. Therefore, it is thought that the stain removal characteristic of fabrics might be due to other characteristics besides fabric density. That is why, hydrophility and luminance of the samples are measured as well. The hydrophility of the samples is expected to be a major factor affecting stain removal characteristics. Hydrophility values present that single jersey, piquet, fleece, and interlock samples are hydrophilic, while 1x1 rib fabric is hydrophobic. However, a consensus about the effect of hydrophility on stain removal can not be reached within this study. The only hydrophobic sample, 1x1 rib, provides lower stain removal results in reflectance and Grey scale grading. Similarly, single jersey, a hydrophilic sample, also presents lower results. A general comment can not be made about the hydrophilic fabrics as well.

Luminance (*L*) values of the samples are quite similar to each other, except for the 1x1 rib sample as seen in Table 2. *L* value of the rib fabric is lower than the other samples. It means that the rib fabric color is a little darker than the others. This may result in a poor reading of stain removal, as the reflectance value may be negatively affected. A darker color may lead to a lower ΔR, even if the stain is well removed. When the result in Table 4 is analyzed, it can be seen that the rib sample presents lower results in ΔR and Grey scale grading.

When the chosen soils are compared, it can be said that tomato paste is the hardest stain to remove, whereas chocolate milk is the easiest according to the results. This outcome is more visible in Grey scale grading and results. As mentioned before, tomato paste and red wine stains are bleachable, whilst chocolate milk is enzymatic. It should be taken into consideration that the detergent used in this study contains enzymes, which may affect the better stain removal results of chocolate milk.

4. CONCLUSION

The subject of staining and removing stains are major concerns for both the professional life of textile academics and the daily life of the public. Literature research in the field of textiles suggests that recent studies generally focus on the effect of various washing parameters on stain removal and stain repellency. Staining characteristics of fabrics have become a popular and important subject in the field of forensic sciences in recent years. Since the evidence in the crime scene examined by the authorities often includes fabrics, staining characteristics of various samples play a major role in forensics. Therefore, some frequently used knitted structures (single jersey, piquet, three-thread fleece, 1x1 rib, and interlock) were stained with commonly seen stains, and the effects of various fabric properties on their stain removal characteristics are investigated in this study. Stain removal performance was evaluated both objectively via a spectrophotometer and subjectively by Grey Scale grading.

Results of ΔR and Grey scale grading presented that, between studied fabrics, 1x1 rib, and single jersey were the most difficult structures for stain removal, whereas piquet fabric was the most convenient. The reason for the poor stain removal characteristic of 1x1 rib fabric is thought to be its structure causing a lower contact area. For the single jersey sample, the lower porosity of fabric and lower air permeability, because of higher fabric density is considered to result in less stain removal. On the other hand, piquet fabric, with its lower fabric density and higher air permeability due to tuck stitches in its structure, provided the best stain removal performance for this study. It can be concluded that tomato sauce is the most difficult stain to remove from the fabric surface, while chocolate milk is the easiest regardless of the structure.

When the results were evaluated, it is observed that fabric structure significantly affects stain removal capacity. Fabric density and air permeability were found to have a significant effect on stain removal, while the influence of the coefficient of friction, hydrophility, and luminance was not evident in this study.

Five different types of knitted fabrics often preferred in casual garments are investigated in this study. It is observed that fabric structure substantially affects stain removal characteristics. Moreover, fabrics have many parameters that may influence their staining properties. Since the staining characteristic of fabrics plays a significant role in forensic science, it may have great importance to establish a database including various fabric types, structures, raw materials, etc. with the collaboration of textile and forensic academics.

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