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Design, production, and mechanical analysis of water-draining symmetrical sandals for slip prevention

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Abstract

Slipping accidents in ablution areas, sometimes leading to serious injuries or death, highlight the need for safer footwear. This study focuses on the design, production, and mechanical evaluation of symmetrical sandals with an elastic rubber-plastic composite base featuring horizontally branched drainage holes in the heel and phalange areas. The goal is to develop a sandal that effectively channels excess water away from the foot, minimizing slip hazards. The methodology includes symmetrical sandal design, mold fabrication, injection molding trials, and mechanical testing. The results indicate that the sandal base exhibits an elasticity range of 8 to 9.5 kg·s/mm, allowing effective water 2/2 drainage. The tensile strength of the straps ranges from 17.1 to 20.8 kgf, surpassing the Indonesian National Standard (SNI 8879:2020) requirement of 12 kgf. These findings suggest that the sandal design enhances safety while maintaining durability.

Keywords:

symmetrical sandals, sandal base molds, sandal strap molds, elasticity level, tensile force.

1 Introduction

Accidents resulting from slips in wudu areas, which can sometimes lead to fatalities, highlight a significant safety issue. In response, the introduction of wudu sandals, certified with Patent Number IDS000005966 and backed by potential investors, presents an opportunity to meet the demand for products that are flexible and can prevent slipping in wet, muddy conditions. This innovation aims to address the needs of users navigating between dry and wet environments, turning a challenge into a valuable opportunity.

To tackle this problem, the design of the sandals has been improved, featuring a volume of approximately 300 ml, which aligns with the capacity of the molding machine for a single injection. This volume is specifically tailored for sandal size 41, representing the average size for adult footwear.

The creation of symmetrical sandals necessitates a set of molds for both the sandal base and the straps. The design incorporates symmetrical elements and elastic requirements by including drainage holes in the sandal base. These holes are strategically placed in the heel and arch areas to facilitate the flow of residual water from ablution. Water that gathers on the foot's surface drains into these two depressions during use. When pressure is applied as the wearer steps down, the excess water is directed outward from the base of the sandal. By lifting the foot again, any remaining water flows back into the basins, allowing for continuous drainage. This design aims to ensure that, after walking a few steps, the water is expelled from the sandal's base, thereby reducing the muddy conditions in the environment.

Wudu sandals possess distinct characteristics that differentiate them from typical flip-flops, necessitating an elasticity test. It is important to note that the Indonesian National Standard (SNI) currently includes only two test parameters, both of which evaluate the force at the front and back of flip-flops. However, testing for elasticity is crucial for wudu sandals; thus, we propose the establishment of a new SNI number dedicated to the elasticity testing of sandal bases.

When a user walks a few steps, any residual water from the wudu washing process can drain from the sides of the sandals. For the production of sandal bases and straps, molds are initially crafted from aluminum. However, for subsequent mass production, utilizing medium carbon material, such as S50C, is more appropriate.

In terms of material properties, sponge rubber with adequate elasticity is essential; it should compress easily underfoot and quickly regain its shape when the foot is lifted. The mold design must accommodate six cores arranged horizontally through the base of the sandal, along with three cores positioned in the heel to create three horizontal drainage holes. Additionally, three cores should be located at the bend of the foot to produce three more horizontal holes. The molds for sandal straps are designed with uniform strap lengths, as the sandals feature a symmetrical design, allowing them to be worn interchangeably on either foot.

Information from the link <https://akses-sni.bsn.go.id/sni> [2] was obtained regarding sandals for the *Standar Nasional Indonesia* (SNI) (Indonesian National Standard), there are only 2 numbers, both of which only test the tensile force of the front sandal strap and back of the two bottom straps of flip flops. Furthermore, information was obtained that the SNI for testing the tensile force of sandal straps was obtained by number SNI 8879:2020 entitled Footwear–Sandals–Quality requirements and test methods. Information was obtained that the force strength of insert-type sandal straps for the front was a minimum value of 12 kgf and for the back strap on the other side. The minimum left-right value is 12 kgf which is tested with a Tensile Testing Machine according to ISO 7500-1 with an accuracy equivalent to 2 and a speed of 100 ± 20 mm/min.

a minimum upper thickness of 1.0 mm, determined by the SNI 12-0902-1989 test method; a minimum breaking stress of 4.0 MPa and minimum elongation at break of 130%, both assessed using the SNI 12-1848-1990 test method; a minimum bottom thickness of 8.5 mm, also verified through the SNI 12-0902-1989 test method; a minimum tear resistance of 3.0 MPa; a maximum Grasselli abrasion resistance of 2.5 mm²/kgm; Shore A hardness ranging from 45 to 75, measured with the SNI 12-1848-1990 test method; a maximum specific gravity of 1.3 g/cm³; and a maximum resistance to tear expansion of 6 mm at 100 kcs, as tested by the SNI 12-1549-1989 test method.

However, neither SNI 8879-2020 nor SNI 12-7074-2005 addresses the elasticity test for sandal bases. For wudu sandals, which require an elastic base to effectively drain residual water after washing, it is essential to develop a new SNI standard to evaluate the elasticity of the sandal base.

The raw material for the sandal base has been made from 60% polyvinyl chloride (PVC) resin which was increased to 70% with the addition of blowing agent (BA) [3] up to an amount of 4% which previously in 2019 had only been tested with the addition of 1% BA. The injection in this study was accompanied by the addition of 2% black dye.

Shoe base mold design measures length = 295 mm, width = 140 mm, height = 109 mm are required mold clamping force 75.21 tons, injection force 68.38 tons for products made of PVC material with a shrinkage factor of 1-2% with a density of 1.1-1.4 g/cm³, and injection temperature at 180°C [4]. A shrinkage factor must be added to the dimensions of the mold so that after the product cools the dimensions are as designed.

When operating a CNC milling machine to create injection molds for bottle caps using aluminum 6061-T6, specific parameters significantly affect the surface roughness of the machining cavity walls. At a cutting speed of 50 mm/min, a machine rotation of 1592 rpm, and a constant depth of cut of 0.5 mm, the average surface roughness achieved was 0.64 mm [5]. Thus, the choice of machining parameters plays a crucial role in determining the surface quality of the mold walls.

For optimal product quality, the mold cavity should be positioned horizontally in the left-right direction. This orientation minimizes product defects, which are influenced by three injection parameters: a temperature of 210°C, a pressure of 42 Bar, and a time of 4.5 seconds [6]. Adhering to these conditions can lead to reduced product defects and increased productivity in polypropylene plastic injection.

In the preparation of PVC plastic, heating in a drying oven at 220°C is critical, especially when working with varying thicknesses from 0.5 to 2.4 mm, with increments of 0.1 mm for each sample. The required heating time ranges from 74 to 162 seconds. Research indicates that excessive heating can lead to dehydrochlorination, resulting in a darker coloration of the PVC material [7]. Therefore, careful monitoring of heating times is essential to avoid compromising the color quality of the PVC.

To ensure a successful injection process, the permitted moisture content for PVC should not exceed 0.08% by weight, with a drying temperature maintained between 60 to 85°C to mitigate the risk of display faults [8]. Prior to injection, it is vital to assess the moisture content and adequately dry the material to reduce splay faults, thereby preserving both quality and aesthetic appearance.

Drying of plastic raw materials can be carried out with a combination of changing the barrel temperature from 180 to 220 °C, screw rotation speed from 75 to 125 rpm, and back pressure from 2 to 6 Bar [9]. Methods other than drying plastic raw materials can save time and production costs.

Some defects occur in the form of flash due to some material sticking to the mold due to seepage of material from the mold cavity along the mold cup line; non-uniform shrinkage, due to different cooling rates; sink marks due to different freezing due to differences in mold wall thickness; unanticipated warpage/distortion of the design; and ejector marks due to small indentation defects affected by ejector thrust [10]. Product defects affect its final appearance and need to be minimized.

Simulations of injection mold design for car door interior panels were carried out with a combination of mold temperature at 76°C, melting temperature at 205°C, cooling time of 23.8s, holding pressure at 54.7MPa, and holding time of 22.1s [11]. These five factors can influence product shrinkage that occurs.

Polypropylene was injected with varying melting temperatures at 155, 160, 165, and 170°C which showed that the injection

results at a low temperature of 155°C, the product was more dominantly defective than the injection at 160 and 165°C and perfect products were obtained at 170°C injection [12]. Adequate melting temperature in injection affects the perfection of the product.

By increasing the melt temperature for polypropylene from 200 to 220°C, the product weight decreases from 31.71 to 31.33 g, and for polystyrene by increasing the melt temperature from 200 to 220°C, the product weight decreases from 48.10 to 47.30 g [13]. The viscosity of plastic melt has a relationship between the melt temperature and the weight injected.

The optimal injection molding parameters were obtained at an injection temperature of 245.3 °C, injection pressure of 79.65 MPa, injection duration of 15.137s, and minimum distortion of 0.4316 mm [14]. The correct influence of temperature, pressure and injection duration produces minimum distortion.

Large injection molds measuring 470 × 270 × 180 mm are difficult to manufacture with metal additive manufacturing technology especially for new products, but provide production cost savings of up to 83.4% and cooling time reductions of up to 94.7% with the wax conformal cooling channel method [15]. The new method proposes significant savings in production costs and cooling time.

The simulation and validation results of cycle time, warpage and shrinkage for injection of plastic products measuring 117 x 93 x 3 mm at a temperature range of 200 and 250 °C showed that the experimental difference was greater than the simulation results of 6.7% for cycle time, and 3.2% for warpage, but the shrinkage of the experimental results is smaller than the simulation results of 8% [16]. Experimental evidence shows results that are quite close to the simulation results.

Injection parameters have been studied by several previous researchers [10-20] to obtain optimal values through various mold design developments and simulations.

The use of recycled PVC materials and their mixtures has been implemented [21] to obtain eco-friendliness and the filling balance has been developed for several injection product branches in one mold [22]. It has been confirmed that Rapid Heat Cycle Molding (RHCM) from numerical and experimental results is valid in reducing short cycle times [23] of plastic products.

The presence of bubble marks on the surface of microcellular type injection molds has been eliminated by dynamic mold temperature control [24]. Traces of surface bubbles can be removed from the gap between the mold and the melt is re-dissolved into the high-temperature melt as the primary means of removal.

Awareness regarding the collection and treatment of plastic waste is a concern in implementing legal limits on waste disposal with a good collection system as a sustainable waste treatment solution [25-27] which is sought to minimize the impact on environmental pollution.

Non-optimization of injection parameters can lead to an increase in flashing defects; however, these defects can be reduced by applying previously determined optimized injection molding parameters [28]. By minimizing flashing defects, production efficiency in the injection of symmetrical sandal products can be enhanced.

Incorporating fillers derived from wood-based materials into polymer composites can significantly improve the mechanical properties of injection-molded products [29]. The careful selection of appropriate filler materials for symmetrical sandals can enhance mechanical properties, particularly the elasticity of the materials, which is crucial for overall performance.

This research was conducted to address product demand from investors and to promote new products that have been registered for patents.

The primary aim of the research is to meet product requirements in accordance with patent criteria, specifically

ensuring that the sandal's base can compress under the weight of the heel (calcaneus) and the bending of the foot (phalanges), while also expanding in elasticity when the foot is lifted.

2 Materials and methods

The materials used in the research are aluminum for sandal base molds and sandal strap molds, steel for the cores for making holes in sandal bases, PVC polymer raw materials with blowing agent (BA), and dyes for sandal base injection and sandal strap injection.

The research method was carried out by designing and making working drawings of patented wudu sandals for adults' size 41, designing and making sandal base molds and sandal strap molds, testing the tensile force of injected sandal straps, testing the elasticity of sandal base, registering patents for elasticity test methods sandal base as a proposed new SNI, and formulation of the elasticity of sandal base which is shown in the flowchart in Fig. 1. The design of the symmetrical sandal product is shown in Fig. 2 with a front view and a top view. The sandal strap mold is shown in Fig. 3 and the sandal base mold is shown in Fig. 4

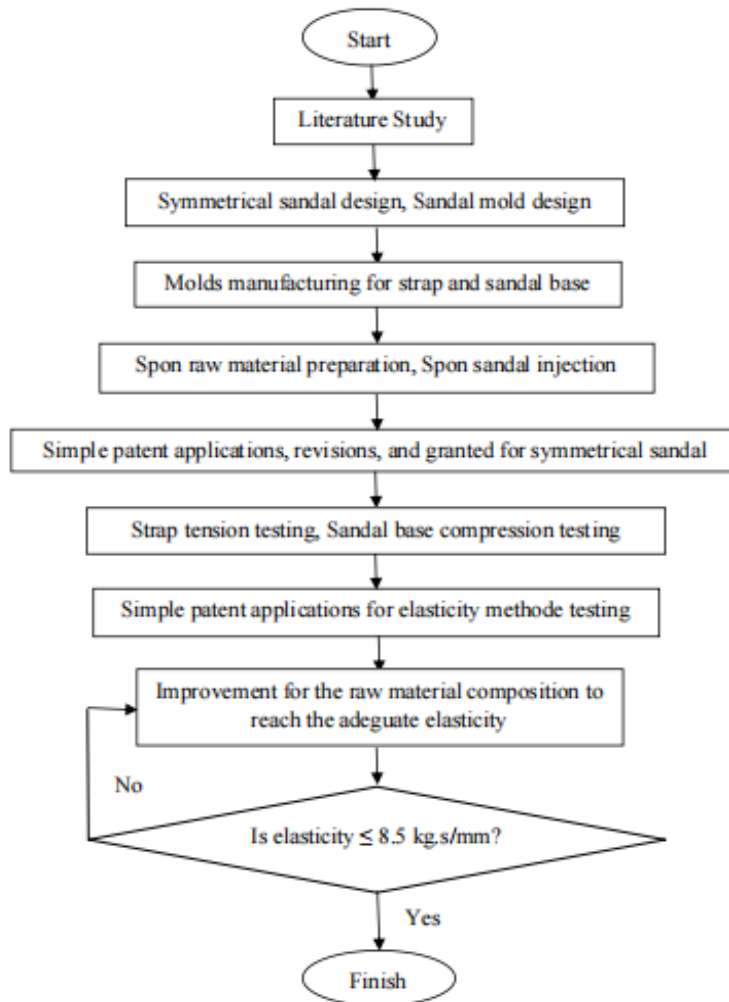


Fig. 1. The flowchart of sandal symmetry research



Fig. 2. Symmetrical sandal product design with front view and top view



Fig. 5. Tensile force test of the front sandal strap



Fig. 3. Sandal strap mold for size 41



Fig. 4. Sandal base mold for size 41



Fig. 6. Tensile force test of left back sandal strap

The tensile force test is shown in Fig. 5, Fig. 6, and Fig. 7 for 5 sandal straps carried out at the Center for Standardization and Services for the Leather, Rubber and Plastic Industry in Yogyakarta, Indonesia with the results are shown in Table 1.



Fig. 7. Tensile force test of the right back sandal strap

The compression test to measure the level of elasticity of the injected sandal base in the heel area is shown in Fig. 8 and the compression test to measure the elasticity level of the injected sandal base in the foot bend area of the foot is shown in Fig. 9.



Fig. 8. Compressive test to measure the level of elasticity of the sandal base resulting from injection in the heel area



Fig. 9. Compressive test to measure the level of elasticity of the sandal base resulting from injection in the bend area of the foot

The elasticity of the sandal base is expressed by Eq. (1). Where m is mass of the object moving in the damping system (kg), a is acceleration of objects moving in the damping system (m/s^2), C is elasticity of moving materials in the damping system (kg/s), V is speed of the mass of moving objects in the damping system (m/s), K is spring constant of the damping system, X is the movement of the spring that is pulled elongated or pressed shorten (m).

$$ma + CV + kX = 0 \quad (1)$$

Because the base of the sandal being tested is in a position on the base of the Tarno Grocki Compression Testing Machine which is stationary, the acceleration (a) is zero = 0, which means $m = 0$ too. So the damping is obtain by Eq. (1):

$$\begin{aligned} CV + kX &= 0 \\ C &= -(kX)/V \\ \text{With } V &= X/t \\ k &= F/X \end{aligned}$$

Because the base of the sandal being tested is in a position on the base of the Tarno Grocki Compression Testing Machine which is stationary, the acceleration (a) is zero = 0, which means $m = 0$ too. So, the damping equation becomes:

$$\begin{aligned} CV + kX &= 0 \\ C &= -(kX)/V \\ \text{With } V &= X/t \\ k &= F/X \end{aligned}$$

So, the elasticity of the sandal sole material is obtained by Eq. (2).

$$\begin{aligned} C &= -(kX)/V = -((F/X)X)/(X/t) \\ C &= -(F.t)/X \text{ (kg.s/mm) or Ns/mm} \end{aligned} \quad (2)$$

The smaller the elastic value of the wudu sandal base in units of kg.s/mm, it means the material is more elastic.

The negative value in the formula indicates the direction of movement of the elasticity of the wudu sandal base which returns to its original thickness, the direction of which is the opposite of the compression direction.

3 Results and discussion

The manufacturing process for symmetrical sandals begins with the design phase, which includes creating working drawings and mold designs for the sandal straps and soles. Next, the

composition of the sponge material is prepared, followed by the injection molding of both the sandal straps and soles. Subsequent testing includes tensile testing of the sandal straps and elasticity testing through compression tests. The elasticity of the straps is measured, and adjustments are made to the raw material composition to achieve the desired elasticity level of 8.5 kg.s/mm. This level is based on the average weight of sandal wearers, representing most users of symmetrical sandals. The sponge material's composition consists of PVC resin, Dioctyl Phthalate (DOP), a Blowing Agent (BA), filler, and dye.

Table 1 presents the results of the tensile tests conducted on the sandal straps. The tensile strength of the front strap ranges from 17.726 to 20.896 kg. The left rear strap exhibits a tensile strength between 17.117 and 18.675 kg, while the right rear strap ranges from 17.968 to 18.494 kg. According to SNI standard number 8879:2020, which stipulates a minimum tensile strength of 12 kgf, all three sandal straps across all sections meet the required standard.

Table 1. Results of symmetrical sandal strap tensile force tests based on SNI 8879:2020

No.	Tensile force (kgf)	Replication					Average
		1	2	3	4	5	
1	Front sandal strap	20.896	18.245	18.668	20.676	17.726	19.242
2	Right rear sandal strap	18.144	18.018	18.494	17.968	18.131	18.151
3	Left rear sandal strap	17.220	18.649	18.675	17.117	17.138	17.760

The results of the sandal pad injection trial with a composition of 94% PVC resin, 4% blowing agent, and 2% black dye, obtained elasticity in the compression test in the heel area and the compression test in the bend area of the foot are shown in Table 2 and Table 3.

Table 2. Results of pressure tests on the heel area of the injection molded sandals

Sandal Base Compression Test on the Heel Area							
Sandal	Replication Test	F (kg)	t (s)	X (mm)	C (kg.s/mm)	Status	Remark
A	1	200	1.21	7.5	32.3	>	Not elastic
	2	190	1.20	7.5	30.4	>	Not elastic
	3	170	1.18	7.5	26.7	>	Not elastic
B	1	200	1.17	7.5	31.2	>	Not elastic
	2	190	1.23	7.5	31.2	>	Not elastic
	3	170	1.20	7.5	27.2	>	Not elastic
C	1	200	1.20	7.5	32.0	>	Not elastic
	2	190	1.24	7.5	31.4	>	Not elastic
	3	170	1.18	7.5	26.7	>	Not elastic
D	1	160	1.23	7.5	26.2	>	Not elastic
	2	140	1.21	7.5	22.6	>	Not elastic
	3	140	1.25	7.5	23.3	>	Not elastic
E	1	200	1.17	7.5	31.2	>	Not elastic
	2	190	1.23	7.5	31.2	>	Not elastic
	3	170	1.26	7.5	28.6	>	Not elastic
F1*	1	50	1.20	7.5	8	=	Elastic
F2*	2	60	1.20	7.5	9.6	=	Elastic

Note: C Standard (kg.s/mm) = $8 \div 9.6$ (kg.s/mm); *Assumption of test results that meet standards.

Table 3. Results of compression tests on the bend area of the foot of injection molded sandals

Sandal Base Compression Test on the Foot Bend Area							
Sandal	Replication Test	F (kg)	t (s)	X (mm)	C (kg.s/mm)	Status	Remark
A	1	250	1.08	7.5	36.0	>	Not elastic
	2	220	1.16	7.5	34.0	>	Not elastic
	3	220	1.22	7.5	35.8	>	Not elastic
B	1	250	1.21	7.5	40.3	>	Not elastic
	2	220	1.32	7.5	38.7	>	Not elastic
	3	220	1.23	7.5	36.1	>	Not elastic
C	1	250	1.31	7.5	43.7	>	Not elastic
	2	220	1.14	7.5	33.4	>	Not elastic
	3	220	1.23	7.5	36.1	>	Not elastic
D	1	250	1.32	7.5	44.0	>	Not elastic
	2	220	1.04	7.5	30.5	>	Not elastic
	3	200	1.13	7.5	30.1	>	Not elastic
E	1	250	1.21	7.5	40.3	>	Not elastic
	2	220	1.24	7.5	36.4	>	Not elastic
	3	220	1.17	7.5	34.3	>	Not elastic
F1*	1	50	1.2	7.5	8	=	Elastic
F2*	2	60	1.2	7.5	9.6	=	Elastic

Note: C Standard (kg.s/mm) = $8 \div 9.6$ (kg.s/mm); *Assumption of test results that meet standards.

The results of the elasticity test on the sandal base resulting from injection with a composition of 94% PVC resin, 4% blowing agent and 2% black dye showed that elasticity in the compression test in the heel area and the elasticity of the compression test in the bend area of the foot still showed results that were not elastic enough. Normal elasticity or standard elasticity for symmetrical sandals is to have an elasticity value of between 8 kg.s/mm and 9.5 kg.s/mm with an average user body weight of 50 to 60 kg. The elasticity test was carried out at a deflection depth of 7.5 mm as a reference with an estimated thickness of the sandal base of 15 mm in both compression test areas.

The method for testing the elasticity of sandal soles has been registered for a Simple Patent with number S00202414022 on November 29, 2024 with the title Method for Testing the Elasticity of Wudu Sandal Bases with Water-Flowing Holes at the Ministry of Law and Human Rights of the Republic of Indonesia.

The tensile test results [3] for PVC sandal base material with a composition of 73% PVC resin, 25% dioctyl phthalate (DOP), 1% blowing agent, and 1% dye yielded a tensile strength of 9.086 MPa. In contrast, a material composition of 83% PVC resin, 15% DOP, 1% blowing agent, and 1% dye resulted in a tensile strength of 13.844 MPa. This data indicates a decrease in tensile strength from 13.844 MPa to 9.086 MPa, or a reduction of 34.4%, due to the increased DOP content from 15% to 25%.

Assuming that the decrease in tensile strength correlates with an increase in the elasticity of the sandal base, one could infer that enhancing elasticity can be achieved by increasing the amount of DOP. Mechanically, elasticity can also be improved by modifying the heel area of the sandal, for instance, by changing the shape of the hole from cylindrical to oval. A longer oval hole would facilitate greater elasticity, as it would require less compressive force. Elasticity is deemed adequate if it falls within the range of 8 to 9.5 kg.s/mm, which corresponds to the weight of a typical sandal user, generally between 50 and 60 kg.

The design of symmetrical sandals necessitates adherence to a new SNI, given the requirement for adequate elastic properties. The pressure applied by a wearer, typically around 55 kg, is

crucial for compressing the sandal sole sufficiently to expel water accumulated from washing. Water trapped in the depressions of the heel area and the arch of the foot can escape through strategically placed holes, which direct the flow to the left and right sides of the sandal base when these areas are stepped on.

4 Conclusion

This research designed and tested symmetrical sandals with an elastic rubber-plastic composite base to improve water drainage and user safety. The main findings include:

1. Strap Tensile Strength testing showed that the tensile force required for detachment or breakage was 19.24 kgf (front), 18.15 kgf (right back), and 17.76 kgf (left back), all exceeding the SNI standard of 12 kgf.
2. The sandal base elasticity which are influenced by material composition (PVC resin, dioctyl phthalate (DOP), blowing agent, filler, and dye), ranged from 8 to 9.6 kg-s/mm will ensure sufficient water drainage.
3. Future Improvements includes optimizing the ratios of PVC resin, DOP, and blowing agents will enhance elasticity and adaptability for users weighing 50–60 kg, ensuring greater comfort and structural integrity for different foot sizes.

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