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Waste Mandarin Peel as an Eco-Friendly Water-Based Drilling Fluid Additive

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Abstract: Drilling fluid represents the most important fluid that must fulfill numerous important assignments during drilling operations. Many commercially available additives for water-based drilling fluid fall into the category of non-degradable and environmentally hazardous materials. Significant development in this area can be made by using biodegradable materials as additives in drilling fluids. The objective of this study was to determine whether mandarin peel powder particle size affects the properties of the drilling fluid. In this paper, mandarin peel was used in the form of a dry powder divided into particle sizes smaller than 0.1 mm, and between 0.1 mm and 0.16 mm. Mandarin peel powder was added to a water-based drilling fluid in four different concentrations (0.5, 1, 1.5, and 2% by volume of water). By increasing the mandarin peel powder concentration, the API filtration reduced up to 42%, PPT filtration significantly decreased up to 61.54%, while the rheological parameters generally increased but remained within acceptable limits. It is determined that the optimal concentration of mandarin peel powder is up to 1.5% by volume of water.

Keywords: circular economy; mandarin peel powder; environmentally friendly additive; drilling fluid; API filtration; PPT filtration; rheological properties

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1. Introduction

During drilling operations, adequate design of the drilling fluid is a very important component. It must fulfill various tasks, such as transporting drill cuttings to the surface, controlling formation pressure, providing lubrication for the drill string, stabilizing the wellbore wall, and many others [1–6]. Drilling fluid is a complex fluid, thus its composition and properties affect the final drilling efficiency. For a successful drilling process, drilling fluid that will meet the conditions specific to each well should be selected [7]. Depending on the liquid phase, which is the basis for the preparation of this type of fluid, drilling fluid is divided into water-based, oil-based, synthetic, and special drilling fluids. Generally, oil-based drilling fluids are usually preferred for HTHP and ultra-HTHP drilling applications. Oil-based drilling fluid provides a high rate of penetration, a reduction in downhole fluid losses, shale stability, and reduced torque and drag [8–11]. However, the use of oil-based drilling fluid has been restricted by strict environmental protection laws due to the high toxicity of oil-based drilling fluid, and its high cost [12].

The problem of environmental protection has resulted in an increase in the use of water-based drilling fluid. Water-based drilling fluid consists mainly of fresh or salt water (>90%), active colloidal particles, inert particles, and chemical additives. Bentonite is an essential component of drilling fluid in water-based systems. It is widely used for its viscosity and filtration control. However, the density of a bentonite suspension is usually not sufficient to control the formation pressure, which means that the desired drilling fluid density must be achieved by the use of weighting agents. Weighting agents, such as barite, hematite, galena, or calcium carbonate, are chemically inert solid particles. Besides bentonite and barite, many other additives are used to control drilling fluid properties. Their classification based on specific functions is shown in Table 1.

Table 1. Drilling fluid additives with specific functions (Adapted from data in [13]).

Type of Additive	Action	Substances (Compounds)
Alkalinity/acidity control additives	Adjusting the pH value.	Lime, sodium hydroxide (caustic soda), sodium carbonate (soda ash), sodium bicarbonate.
Bactericide (biocide)	Killing bacteria in water-based drilling fluid containing natural starches and gums prone to bacterial degradation.	Aldehides, phenols.
Calcium reducers	Reducing Ca^{2+}.	Sodium hydroxide (caustic soda), sodium carbonate (soda ash), sodium bicarbonate, polyphosphates.
Corrosion inhibitors	Protecting equipment from corrosion.	Amine or organophosphate products, oxygen scavengers.
Deflocculants (thinners)	Reducing viscosity, preventing flocculation.	Low-molecular-weight anionic polymers. Tannins, polyphosphates, lignite, lignosulfonate.
Defoamers	Removing entrapped air and gas from drilling fluid systems.	Alcohol based defoamers, brine-based defoamer, acid fat based defoamers, silicone emulsion based defoamers.
Emulsifiers	Forming emulsion of two insoluble liquids.	Detergents, soaps, organic acids.
Filtration reducers	Reducing infiltration of the liquid phase of the drilling fluid through the filter cake into the formation.	Bentonite clays, lignite, CMC, polyacrylate, pregelatinized starch.
Flocculants	Causing flocculation of colloidal particles.	Salt hydrated lime, gypsum, sodium carbonate (soda ash), soda bicarbonate, sodium tetraphosphate, acrylamide-based polymers.
Foaming agents	Acting as surface active agents to foam into water.	Nonionic surfactants, contain polymeric materials.
Lost circulation materials	Bridging for fluid lost control.	Fiber, flake, granular/chemical thickening agents.
Lubricants	Reducing fluids coefficient of friction to minimize torque and drag.	Oils, synthetic liquids, graphite, surfactants, glycols, glycerine.
Shale inhibitors	Reducing shale hydration.	Soluble calcium or potassium, inorganic salts, organic compounds.
Surfactants	Surface tension decreasing, changing the colloidal state of clay.	Emulsifiers, demulsifiers, wetting agents, flocculants, deflocculants
Viscosifiers	Increasing viscosity, improving the hole-cleaning and solids-suspension ability.	Clay-based viscosifiers (bentonite), polymer and biopolymer viscosifiers.
Weighting agents	Increasing density of drilling fluid.	Barite, hematite, galena, calcium carbonate.

Focus on economics and performance in drilling activities and marginalization of environmental care has resulted in the use of toxic chemical additives in conventional water-based systems. These additives include sodium hydroxide, potassium chloride, potassium sulphate, polyamine, chromium-containing thinners, many shale stabilizers, and fluid loss additives, etc. [14–16]. Many commercially available additives for water-based drilling fluid fall into the category of non-degradable and environmentally hazardous materials [17]. There is a need to find and create new environmentally friendly additives that will contribute to the control of the drilling fluid properties in the same way, but with minimal impact on the environment [18,19]. Therefore, many studies have been and are still being conducted on using food waste [20] and other biodegradable materials as additives.

According to the World Bank, the world annually generates 2.01 billion tonnes of municipal solid waste (0.74 kg per person per day), of which 44% are food and green waste. By 2050 it is expected to grow up to 3.40 billion tonnes annually [21], which encouraged people to think about potential uses of food waste in order to reduce its amount, and at the same time obtain usable products. This requires a necessary change of a linear product lifecycle model, which has been applied thus far to an economy of reusing, remanufacturing, and recycling. In line with that, The European Green Deal, a new agenda for sustainable growth, requires global transition to a carbon-neutral, resource-efficient, and circular economy; this would reduce pressure on natural resources and energy consumption, while at the same time enable sustainable growth and new job creation. As one of its main strategy pillars, in 2020, the European Commission adopted the New Circular Economy Action Plan (CEAP). The plan oversees the entire life cycle of products, including their design, sustainable consumption, and waste prevention, bearing in mind that ways which imitate nature, where everything has value, are recognized as the only possible ways to reach a balance between progress and sustainability [22–24]. At the same time, the competitiveness of the oil industry in the world, where environmental protection has become a priority, depends on their adaptation possibilities. Oil companies are more concerned with their public images than ever before, and therefore are faced with inventing sustainable and environmentally friendly solutions which can ensure their survival. Significant development in this regard can be made with additives that are used in drilling fluid, for certain properties.

In the last few years, researchers have begun to undertake laboratory testing to determine whether food waste materials can be used as additives in water-based drilling fluids, in order to optimize the composition and properties of drilling fluids. As shown in Table 1, there are many additives on the market used to adjust different drilling fluid properties. However, most of the research relates to the possibility of using waste materials as additives to adjust the rheological and filtration properties. Table 2 shows eco-friendly water-based drilling fluid additives used thus far in tests, with their indicated influence on rheological parameters (plastic viscosity (PV), yield point (YP)), gel strength, API filtration, and drilling fluid cake thickness.

Rheological parameters are especially important since they affect cutting removal from the wellbore to the surface, resistance to drilling flow, and an increase in wellbore pressure, keeping cuttings and weighting additives in suspension during the period of circulation interruption, in addition to cutting release on the surface [25]. Plastic viscosity (PV) is a function of friction between solid particles in a drilling fluid, the amount of charge on these particles, and the viscosity of the dispersed phase. Yield point (YP) is a function of force between solid particles in the drilling fluid, and represents the capability of a drilling fluid to remove the cuttings from the annular space of the wellbore. Gel strength should be measured after 10 s and 10 min. Results obtained after 10 s (initial gel strength) show the minimum required shear stress to initiate fluid movement, and after 10 min indicate a measure of the thixotropic property of drilling fluid.

Filtration is the process of liquid phase separation from a drilling fluid into porous formation by the influence of differential pressure. Filtration rate and filtrate volume are directly related to the drilling rate, type of formation, formation damage, and differential sticking in the area of permeable rocks [26,27]. Generally, filtration can be defined as a measure of the drilling fluid's ability to cover a permeable formation with a thin and low-permeability cake.

In order to obtain a more pronounced effect of each additive on the properties of the drilling fluid, most of the tests are performed using a basic drilling fluid that contains only bentonite in addition to water. The waste materials are added in different concentrations (from 0.285% up to 16%), but in most cases small concentrations are added up to 4% by volume of water, as shown in Table 2.

Al-Hameedi et al. (2020) conducted laboratory testing with mandarin peel which was added to base drilling fluid that contained 600 mL water, 0.6 g NaOH, and 36 g of bentonite. Mandarin peel powder was added in four different concentrations: 1%, 2%, 3%, and 4% by volume of water. Rheological parameters, plastic viscosity (PV), and yield point (YP) were increased by adding mandarin peel powder. After adding 1% mandarin peel powder to a base drilling fluid, plastic viscosity increased from 7 mPa·s to 14 mPa·s, and continued to increase to 63 mPa·s with 4% of mandarin peel powder in the base drilling fluid. Yield point also increased from 5.61 Pa to 7.14 Pa with 1% of mandarin peel powder, and with 4% of mandarin peel powder in the base drilling fluid, the value of yield point was 29.07 Pa, which in practice results in excessive pressure loss. The results for 10-s gel strength showed a slight decrease by adding 1% and 2% of mandarin peel powder to the base drilling fluid, and an increase after adding 3% and 4%, with a maximum value of 12.24 Pa. The same trend was shown with results for 10-min gel strength, and the value was 14.18 Pa with 4% of mandarin peel powder in the base drilling fluid. API filtration with 1% mandarin peel powder significantly decreased from 12.5 mL to 7 mL, and by increasing the concentration to 4%, it continued to slightly decrease to 4 mL [28].

In 2020, mandarin production in Croatia was 38,172 tonnes [29]. In this study, from 1 kg of mandarin fruit, 72 g of mandarin peel powder was obtained, which leads to the conclusion that approximately 2750 tonnes of mandarin peel powder can be generated in Croatia every year. According to Al-Hameedi et al. (2020), the maximum concentration of mandarin peel powder was 4% by volume of water [28], but in this paper the highest tested concentration of mandarin peel powder was 2%; by increasing the concentration above 2%, considerable drilling fluid gelation occurred, and it was impossible to mix it. If it is considered that the required concentration of mandarin powder is 2%, based on the annual mandarin production in Croatia, about 137,500 m^3 of drilling fluid can be prepared. Mandarin peel waste generated annually in Croatia can be transformed into powder and used as a drilling fluid additive for more than 150 wells, which is much more than the domestic requirements.

Also, it is important to note that drilling operations generate a significant volume of drilling fluid waste that has to be properly treated and disposed of during and after drilling operations. Used drilling fluid represents the second largest volume of waste generated by the exploration and production part of the oil and gas industry [30,31]. Along with environmental protection, there is also significant cost for the disposal of environmentally hazardous waste. At some locations, there are other options for managing these types of waste, such as injection in deep underground formations [31–34]; waste optimization and reduction in waste volume to a minimum should be priorities [35].

In this paper, mandarin peel powder was used to determine its influence on rheological and filtration properties of bentonite-based drilling fluid. This type of food waste was chosen since mandarin is in second place in terms of fruit production in Croatia [29], and since other authors have found some useful properties of mandarin peel powder as an additive in drilling fluid [28,36,37].

The objective of the study was to determine whether mandarin peel powder particle size affects the properties of the drilling fluid. Compared to the research conducted by Al Hameedi et al. (2019 and 2020), the novelty of this research is manifested in a new detailed procedure of mandarin peel powder preparation (drying, grinding, sieving), as well as in the determination of the influence mandarin peel powder particle size (smaller than 0.1 mm, and between 0.1 and 0.16 mm) has on rheological and filtration properties (API filtration tests and PPT filtration tests (high pressure and high temperature conditions)).

Table 2. Eco-friendly water-based drilling fluid additives and their impact on drilling fluid properties.

Literature	Waste Material	Concentration, % by volume of Water	Tested Drilling Fluid Formulation	Rheology		Gel Strength	API Filtration	Cake Thickness
				Plastic Viscosity (PV)	Yield Point (YP)			
Al-Hameedi et al., 2019 and 2020 [16,28,36,37]	potato peel	1, 2, 3, 4	600 mL water, 0.6 g NaOH, 36 g bentonite	increase	decrease	decrease	decrease	decrease
	mandarin peel			increase	increase	up to 2% decrease, then increase	decrease	decrease
	fibrous food	1, 2	1000 mL water, 0.6 g NaOH, 60 g bentonite	increase	increase	increase	decrease	decrease
	palm tree leaves	1.5, 3	600 mL water, 1 g NaOH, 45 g bentonite	increase	decrease	decrease	decrease	decrease
	grass	0.5, 1, 1.5	spud drilling fluid	increase	increase	increase	decrease	decrease
	green olive pits	0.75 and 1.5	600 mL water, 0.6 g NaOH, 36 g bentonite	increase	increase	increase up to 0.75%, then decrease	decrease up to 0.75%, then increase	increase
Ghaderi et al., 2020 [3]	saffron purple petals	1, 2, 3	500 mL water, 0.03 wt% soda ash, 0.05 wt% NaOH, 3.5 wt% NaCl, 10 wt% bentonite	increase	increase	N/A	decrease	decrease
Al-Saba et al., 2018 [38]	banana peel	0.285, 0.57, 1.425	325.5 mL water, 24.5 g bentonite	significantly increase up to 0.285%, then significantly decrease	significantly increase up to 0.285%, then significantly decrease	significantly increase up to 0.285%, then signifi-cantly decrease	decrease	decrease
	olive pulp	0.57		increase	increase	increase	decrease	increase
	corncob	0.57, 1.71, 2.85		increase	increase	increase	decrease	decrease
	corn starch	0.57		decrease	increase	increase	decrease	decrease
	pomegranate peel	0.57		decrease	decrease	decrease	decrease	decrease
	tamarind gum	1.425, 2.85		N/A	N/A	N/A	decrease	decrease
	peach pulp	1.425		decrease	increase	increase	decrease	decrease
	coconut coir	1.425		N/A	N/A	N/A	increase	decrease
	soya bean peel	1.425		N/A	increase	increase	decrease	decrease
	sugar cane	1.425		increase significantly	increase	increase	decrease	decrease
	grass	1.425		increase	decrease	increase	increase	decrease
	henna	1.71, 2.85		increase	increase	increase	decrease	decrease
	coconut shell	1.71, 2.85		increase	increase	increase	decrease	decrease
Zhang et al., 2020 [39]	pomelo peel	1	600 mL water, 18.6 g bentonite	decrease	decrease	N/A	decrease	N/A

Table 2. *Cont.*

Literature	Waste Material	Concentration, % by volume of Water	Tested Drilling Fluid Formulation	Rheology		Gel Strength	API Filtration	Cake Thickness
				Plastic Viscosity (PV)	Yield Point (YP)			
Al-Hameedi et al., 2020 [40]	egg shell	0.75, 1.5	700 mL water, 0.2 g NaOH, 42 g bentonite	increase	increase	increase	decrease	decrease
Onolemhemhen et al., 2019 [41]	egg and snail shell	1.43, 2.86, 4.29, 5.71, 7.14, 8.57	350 mL water, 25 g bentonite, 90 g barite	N/A	N/A	N/A	N/A	N/A
Yalman et al., 2021 [42]	rice husk ash	2.1, 4.3, 7.5, 9.6, 13.4, 16	350 mL water, 22.5 g bentonite, 0.5 g xanthan gum (XG), 1 g carboxymethyl cellulose (CMC)	decrease	increase	increase	decrease up to 9.6%, then increase	increase

2. Laboratory Testing

The impact of adding mandarin peel powder to a bentonite-based drilling fluid on rheology and filtration properties was performed at the Drilling Fluid Laboratory (Department of Petroleum and Gas Engineering and Energy, Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb) in Zagreb, Croatia.

2.1. Preparation of the Mandarin Peel Powder

This paper presents the use of mandarin peel powder as an additive used to optimize drilling fluid properties without environmental problems. The entire process of preparing mandarin powder from waste collection, to drying and grinding, is shown in Figure 1.

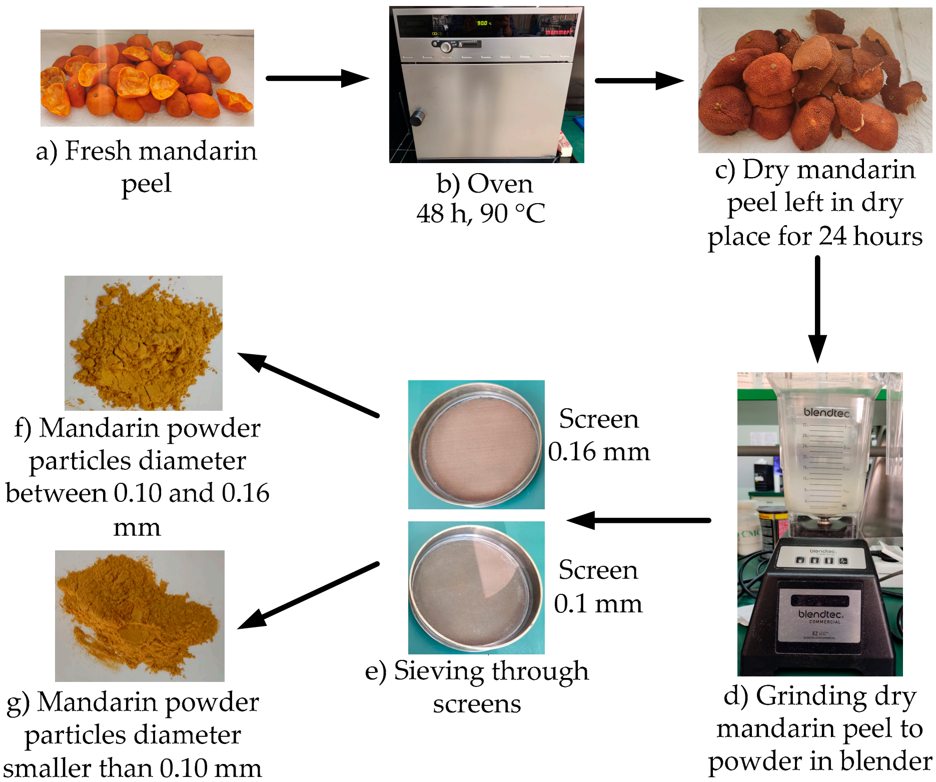


Figure 1. The entire process of preparing waste mandarin peel powder from waste collection.

After the waste mandarin peel was collected (a), it was first placed in an oven for 48 h at a temperature of 90 °C (b) in order to remove moisture from the peel. After 48 h of drying, the peel was left in a dry place for 24 h (c) and then ground and turned into powder using a blender (d). The resulting powder was sieved through two screens, first through one which had a 0.16-mm opening on the sieve (e). The particles that passed through this screen went to the next stage of sieving through a screen which had a 0.10-mm opening on the sieve (e). Thus, mandarin peel powder was divided into two groups of particle sizes, from 0.10 mm to 0.16 mm (f), and particles smaller than 0.10 mm (g). Mandarin peel powder of different particle sizes was used to check whether there were any differences in their useful properties for basic drilling fluid.

2.2. Drilling Fluids Composition

In order to examine the impact of the addition of mandarin peel powder on the rheological and filtration properties of bentonite-based drilling fluids, nine types of drilling fluids were prepared and subjected to laboratory testing: bentonite-based drilling fluid as a base drilling fluid (BDF), four drilling fluids containing mandarin peel powder with particles smaller than 0.1 mm (labelled with A), and four drilling fluids containing mandarin peel powder with particles between 0.1 and 0.16 mm (labelled with B), as shown in Table 3. The mandarin peel powder was added in four different concentrations: 0.5, 1, 1.5, and 2% by volume of water, in order to determine the influence of concentration and particle size on drilling fluid properties. Drilling fluids with 4% mandarin powder were also prepared, but they gelled very quickly, and it was impossible to mix them further; hence, the maximum selected concentration was 2% by volume of water. Drilling fluids were prepared according to American Petroleum Institute Standards, API Specifications 13A and API 13B-1 [43].

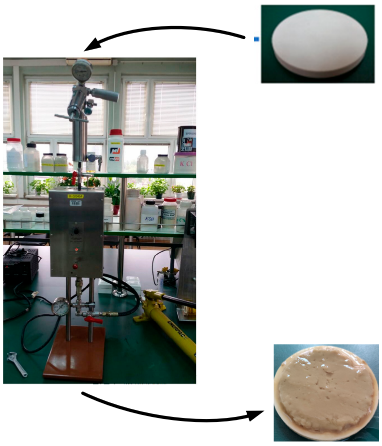
Table 3. Composition of drilling fluids used in this study.

Composition	BDF	A1	A2	A3	A4	B1	B2	B3	B4
Water (mL)	1000	1000	1000	1000	1000	1000	1000	1000	1000
Bentonite (g)	60	60	60	60	60	60	60	60	60
NaOH (g)	1	1	1	1	1	1	1	1	1
Mandarin peel powder (% by volume of water)	-	0.5	1	1.5	2	0.5	1	1.5	2

2.3. Laboratory Test Equipment and Conditions

After preparation of the drilling fluids, filtration and rheological properties, in addition to gel strength, were measured for all nine drilling fluids. The equipment and conditions used are shown in Table 4.

Table 4. Laboratory test equipment and conditions.

Test	API Filtration	PPT Filtration	Rheology and Gel Strength
Equipment	 API Filter Press (Baroid, Houston, TX, USA)	 Permeability Plugging Tester (OFI Testing Equipment, Houston, TX, USA)	 Fann Viscometer 35 A (Fann Instruments, Houston, TX, USA)
Conditions	Pressure of 6.895 bar (100 psi) and room temperature	Differential pressure of 34.47 bar and temperature of 88 °C	Atmospheric pressure and room temperature

3. Results

3.1. API and PPT Filtration

Filter paper Whatman No. 50 with a filtration area of 45.8 cm^2 (7.1 in^2) was placed in the bottom of the API filter press cell. After preparation of drilling mud, it was poured into a cell. A pressure of 6.895 bar (100 psi) was applied to the drilling fluid for a period of 30 min. The volume of filtrate extracted from the drilling fluid through the filter paper was gathered in a measuring cylinder, while a drilling fluid cake was formed on the filter paper. Filtrate volume measured after 30 min represents API filtration.

Based on the results of API filtration, by increasing the mandarin powder concentration the API filtration reduces, as shown in Table 5. The lowest API filtration was measured with B4 drilling fluid (10 mL), relative to a value measured with BDF (18 mL). The drilling fluid cake thicknesses were slightly reduced by the addition of mandarin peel powder compared to the drilling fluid cake thickness measured with BDF (1.5 mm).

A device used for determining the ability of the drilling fluid to plug pores in a ceramic disc is called a Permeability Plugging Tester (PPT), which represents a modification of the standard HTHP filter press. After preparation of drilling mud, it was poured into a PPT cell. The required pressure is applied with a pump on the lower side, which pushes the mud through a ceramic disk placed on the upper side of the cell. The filtrate was collected in a receiver after 7.5 and 30 min. The filtration area is 22.9 cm^2 (3.5 in^2), twice as low as that of API filtration, and the filter medium is a ceramic disc. The permeability of used ceramic discs was 0.75 μm^2 (750 mD), and the tests were carried out at a differential pressure of 34.47 bar and a temperature of 88 °C. Since the filtration surface in API filtration is twice as large, fluid volume collected after 30 min needs to be multiplied by 2 (Equation (1)), while the initial filtration or spurt loss can be calculated using Equation (2) [44]:

$$\text{PPT filtrate volume} = 2 \cdot V_{30} \tag{1}$$

$$\text{Spurt loss} = 4 \cdot V_{7.5} - 2 \cdot V_{30} \tag{2}$$

where:

PPT filtrate volume, mL;

$V_{7.5}$—fluid volume collected after 7.5 min, mL;

V_{30}—fluid volume collected after 30 min, mL;

Spurt loss—fluid volume collected before forming a drilling fluid cake, mL.

The PPT filtration test was performed only with those drilling fluids where the greatest reduction in API filtration was measured for both tested mandarin peel particle sizes, which were the A4 and B4 drilling fluids. Table 6 shows the results of PPT filtration through a ceramic disc with a permeability of 0.75 μm^2 (750 mD).

Table 5. API filtration.

Time (min)	BDF	A1	A2	A3	A4	B1	B2	B3	B4
	API Filtration (mL)								
2.5	5.5	4.5	4	3	3.5	4.5	4	3	2.5
5	7.5	5.5	5.5	4.5	4.5	6.5	5.5	4.5	3.5
7.5	9.5	7	6.5	5.5	5.5	7.5	6.5	5	4.5
10	10.5	8	8	6.5	6.5	9	7.5	6	5.5
12.5	12	9	9	7.5	7.5	10.5	8.5	6.5	6.5
15	13	10	9.5	8	8	11.5	9	7.5	7
17.5	14	10.5	10.5	8.5	9	12	10	8	7.5
20	15	11	11	9	9.5	13	10.5	8.5	8
22.5	16	12	12	10	10	14	11	9	8.5
25	17	12.5	12.5	10.5	10.5	14.5	11.5	9.5	9
27.5	17.5	13	13	11	11	15	12	10	9.5
30	**18**	**13.5**	**13.5**	**11.5**	**11.5**	**16**	**13**	**10.5**	**10**

Table 6. PPT filtration through a ceramic disc with a permeability of 0.75 μm^2 (750 mD).

	Disc Permeability—0.75 μm^2 (750 mD) Differential Pressure—34.47 bar		
	Temperature—88 °C		
Drilling fluid	BDF	A4	B4
Concentration of mandarin peel powder, % by volume of water	0	2	2
$V_{7.5}$, mL	17	8	6
V_{30}, mL	26	11	10
PPT filtrate volume, mL	52	22	20
Spurt loss, mL	16	10	4

Filtration through the ceramic disc, which has a permeability of 0.75 μm^2 (750 mD), showed a significant decrease in filtration volume after 30 min for both tested drilling fluids containing mandarin peel powder in a concentration of 2% by volume of water (A4 and B4) (20 and 22 mL), relative to values measured with BDF (52 mL). Observing the spurt loss values, the amount of fluid that was lost before forming the drilling fluid cake was significantly decreased for both tested drilling fluids containing mandarin peel powder in a concentration of 2% by volume of water (A4 and B4) (4 and 10 mL), relative to values measured with BDF (16 mL). Since the tested disk has pores of different sizes, it is assumed that mandarin peel particles (particles between 0.1 and 0.16 mm) better plugged the disc pores relative to particles smaller than 0.1 mm where a certain amount of these particles passed through the disc before forming the drilling fluid cake.

3.2. Rheology of Tested Drilling Fluids

The rheological properties of all tested drilling fluids were determined using a Fann viscometer 35A. Shear stresses were obtained at six fixed speeds of 600, 300, 200, 100, 6, and 3 rpm. The plastic viscosity (PV) of all the tested drilling fluids was calculated according to Equation (3), and the yield point (YP) was calculated according to Equation (4) [45]:

$$PV = \theta_{600} - \theta_{300} \quad (3)$$

$$YP = 2 \cdot \theta_{300} - \theta_{600} \quad (4)$$

where, θ_{600} and θ_{300} are the 600 and 300 RPM dial readings, respectively.

The results of plastic viscosity (PV) and yield point (YP) are shown in Figure 2, YP/PV ratio in Figure 3, while results of 10-s gel and 10-min gel strengths for all tested drilling fluids are shown in Figure 4.

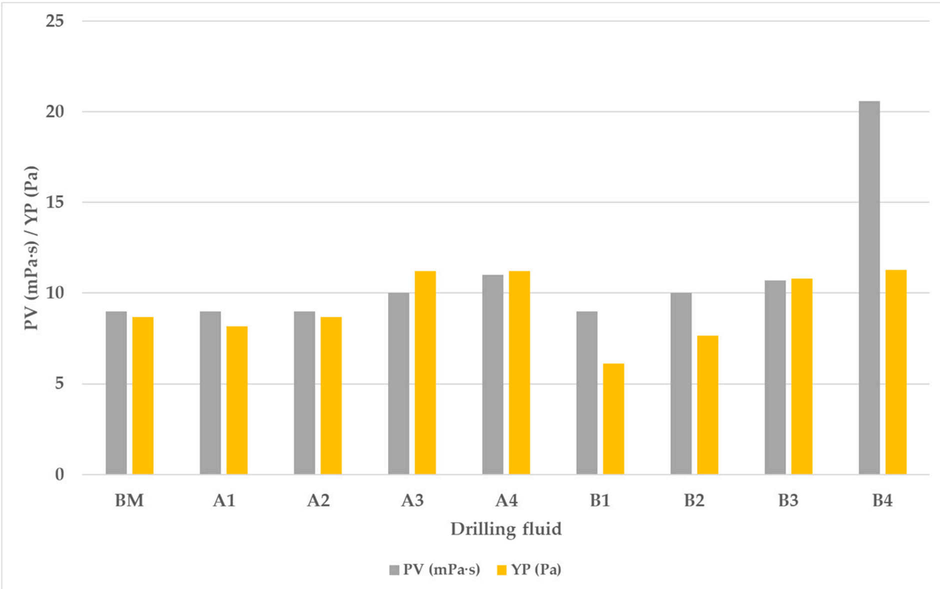


Figure 2. Plastic viscosity (PV) and yield point (YP) of all tested drilling fluids.

It was determined that increasing the concentration of mandarin peel powder generally increases all the values of rheological parameters (PV and YP) and the 10-s gel and 10-min gel strengths. The highest values of rheological parameters (PV and YP) were measured with A4 and B4 drilling fluids (11 mPa·s and 11.22 Pa, and 21 mPa·s and 11.27 Pa, respectively), relative to values measured with BDF (9 mPa·s and 8.67 Pa, respectively). By increasing the YP/PV ratio, the cutting carrying capacity of the drilling fluid increased [46]. It is shown that by addition of mandarin peel powder in a concentration of 1.5% by volume of water and higher, the cutting carrying capacity increases. The exception is B4 mud, since it has a high PV value and therefore a smaller value of YP/PV. Moreover, the highest values of 10-s gel and 10-min gel strengths were measured with A4 and B4 drilling fluids (10.71 Pa and 18.36 Pa, and 12.75 Pa and 22.95 Pa, respectively), relative to values measured with BDF (6.12 Pa and 15.81 Pa, respectively).

In order to explain in more detail, the influence of concentration of mandarin peel powder on the rheological properties of the drilling fluid, the pressure loss values in annular (per 1 m of pipe length) were determined for all tested drilling fluids, which can be seen in Table 7. The pressure loss around the drill pipes and drill collars was calculated for the case when wellbore was drilled with a bit having a diameter of 0.2159 m (8 1/2 in). Drill collars had an outside diameter of 0.17145 m (6 3/4 in), and drill pipes had an outside diameter 0.127 m (5 in). The drilling fluid pump flow rate was 1600 L/min.

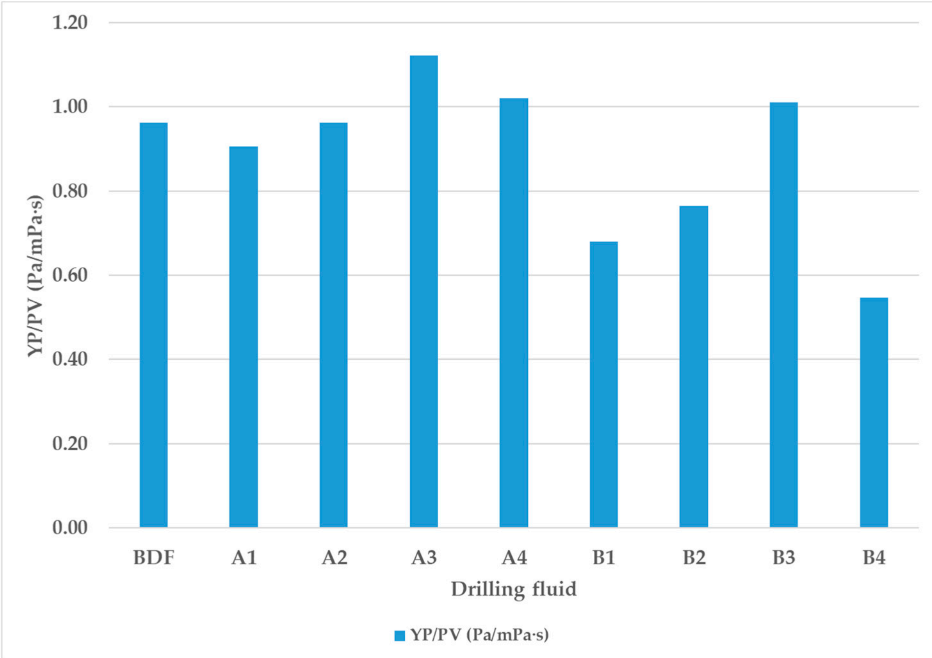


Figure 3. YP/PV ratio of all tested drilling fluids.

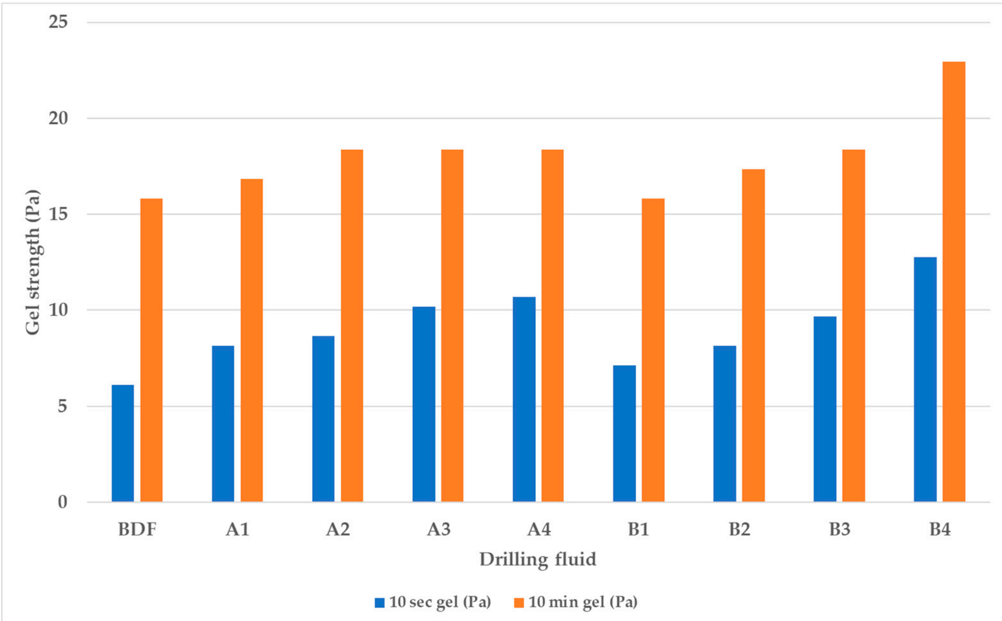


Figure 4. The 10-s gel and 10-min gel strengths of all tested drilling fluids.

Table 7. Pressure loss per 1 m of pipe length.

Drilling Fluid Flow	BM	A1	A2	A3	A4	B1	B2	B3	B4
	Pressure Loss (Pa/m)								
Around drill pipe	451	428	451	572	579	336	411	458	567
Around drill collar	1821	1821	1807	1846	1866	1821	1846	1846	2012

The density of the basic drilling fluid (BDF) was 1030 kg/m^3, while the addition of mandarin powder slightly reduced its value up to 1010 kg/m^3, at a maximum tested concentration of mandarin peel powder of 2% by volume of water. The main reason for the decrease in the density of the drilling fluid is the entry of air into drilling fluid during the mixing. Al-Hameedi et al. (2020) noticed the same phenomenon [28].

With the stated geometry of the wellbore, geometry of used drilling tools, and the flow conditions, the flow around the drill pipes was laminar, and around the drill collars turbulent, as shown in Figure 5.

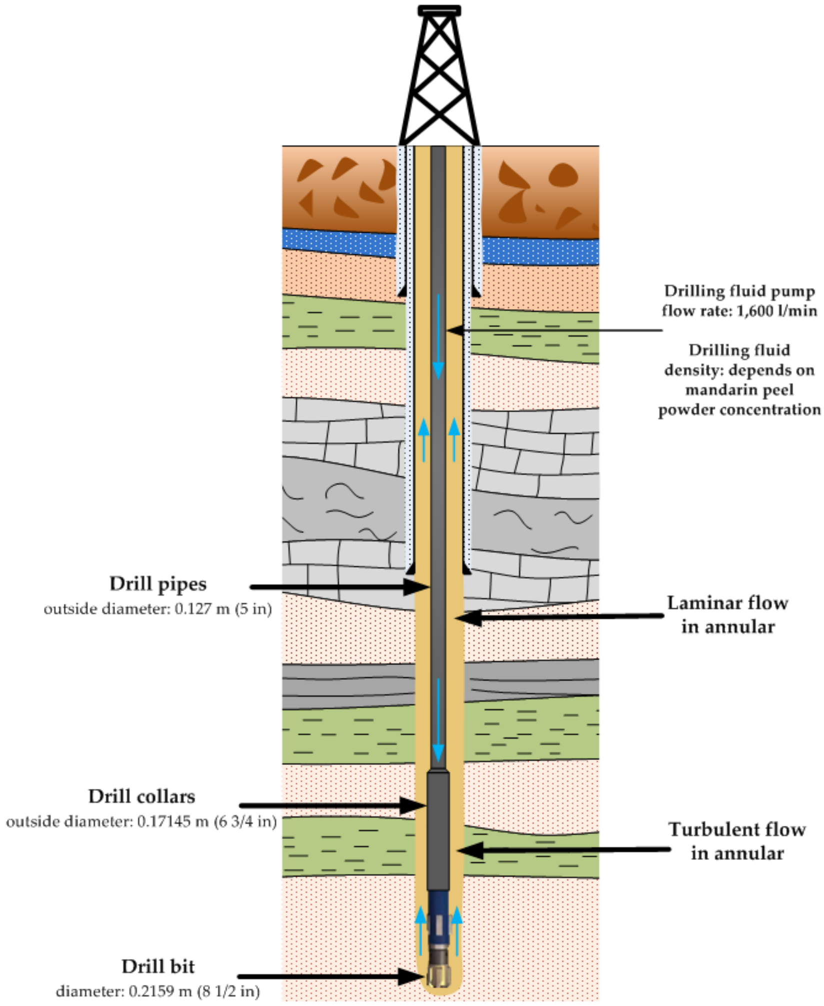


Figure 5. Input data for the calculation of the pressure loss in the annular.

For laminar flow the pressure loss is calculated according to Equation (5), while for turbulent flow is calculated according to Equation (6) [47]:

$$p = \frac{48 \cdot l \cdot \mu_e \cdot v}{(D_2 - D_1)^2} \tag{5}$$

$$p = \frac{0.1275 \cdot l \cdot \rho_i^{0.8} \cdot v^{1.8} \cdot {\mu_e}^{0.2}}{(D_2 - D_1)^{1.2}} \tag{6}$$

where:

v—flow rate of the drilling fluid in the annular space (m/s);
ρ_i—drilling fluid density (kg/m^3);
μ_e—effective viscosity (Pa·s);
D_2—drill bit diameter or inside diameter of casing (m);
D_1—outside diameter of drill pipe/collar (m);
l—pipe length (m).

For a turbulent type of flow, the effective viscosity value is the same as PV, while for laminar flow, it is calculated according to Equation (7) [47]:

$$\mu_e = PV + \frac{YP}{\frac{12 \cdot v}{D_2 - D_1}} \quad (7)$$

where:

v—flow rate of the drilling fluid in the annular space (m/s);
PV—plastic viscosity (Pa·s);
YP—yield point (Pa);
D_2—drill bit diameter or inside diameter of casing (m);
D_1—outside diameter of drill pipe/collar (m).

As expected, it is shown that generally pressure loss increases by increasing the concentration of mandarin peel powder for flow around the drill collar. For laminar flow, an increase in pressure loss was observed at higher concentrations than 1.5% of mandarin powder while at lower concentrations (below 1% of mandarin peel powder) it is even less than the pressure loss calculated with basic drilling fluid (BDF).

4. Discussion

To determine the influence of the concentration and particle size of mandarin peel powder, a comparison of all results was made. Table 8 shows a reduction in API filtration for all tested drilling fluids relative to API filtration of base drilling fluid (BDF), expressed as percentages.

Table 8. Reduction in API filtration for all tested drilling fluids.

Drilling Fluid Sample	Reduction in API Filtration (%)
A1	25
A2	25
A3	36
A4	36
B1	11
B2	28
B3	42
B4	44

It is shown that the highest reduction in filtrate volume was obtained with drilling fluids which contain large amounts of mandarin peel powder (2%), drilling fluids A4 and B4; meanwhile, the highest value was obtained with B4 drilling fluid (44%) which contains larger particles (between 0.1 and 0.16 mm). Comparing results obtained at the concentrations of 1, 1.5, and 2% of mandarin powder, better results were obtained with powder having larger particles (between 0.1 and 0.16 mm) (28%, 42%, and 44%, versus 25%, 36%, and 36%, respectively).

Table 9 shows a reduction in PPT filtration and spurt loss for A4 and B4 drilling fluids relative to values measured with base drilling fluid (BDF), expressed as percentages.

Table 9. Reduction in PPT filtration and spurt loss for all tested drilling fluids.

Drilling Fluid	Reduction in PPT Filtration (%)	Reduction in Spurt Loss Volume (%)
A4	57.69	37.5
B4	61.54	75

It is shown that PPT filtration and spurt loss significantly decreased for both tested drilling fluids (A4 and B4), compared to values measured with a base drilling fluid (BDF). Comparing both results, better results were obtained with powders containing larger particles (between 0.1 and 0.16 mm). Although a slight decrease in PPT filtration was observed (61.54% compared to 57.69%), the value of spurt loss was significantly reduced (75% compared to 37.5%).

Table 10 shows an increase/decrease in rheological parameters and gel strength values relative to values obtained with base drilling fluid (BDF), expressed as percentages.

Table 10. Increase/decrease values of rheological parameters.

Parameter	Increase (+)/Decrease (−) (%)							
	A1	**A2**	**A3**	**A4**	**B1**	**B2**	**B3**	**B4**
PV (mPa·s)	0	0	11	22	0	11	19	129
YP (Pa)	−6	0	29	29	−29	−12	25	30
YP/PV (Pa/mPa·s)	−6	0	16	6	−29	−21	5	−43
10 s gel (Pa)	33	42	67	75	17	33	58	108
10 min gel (Pa)	6	16	16	16	0	10	16	45

By increasing the concentration of mandarin peel powder, plastic viscosity increased slightly up to a concentration of 1.5%. For drilling fluids containing larger mandarin particles (between 0.1 and 0.16 mm), after increasing the mandarin peel powder concentration up to 2%, a significant increase in PV (129%) was obtained. Generally, particle size does not have much of an impact on PV, since up to a concentration of 1.5% similar values were obtained.

Yield point values at concentrations up to 1% are even smaller than those obtained with BDF, while at higher concentrations they follow the results of plastic viscosity such that increasing the concentration increases its values. When comparing the influence of particle size on YP values, it is shown that similar values were obtained at concentrations of 1.5 and 2% by volume of water.

YP/PV ratio has a similar trend as the YP value, with the exception of B4 mud where a significant increase in PV was obtained (129%). It can be seen that for improving the cutting carrying capacity, concentration of mandarin peel powder should be 1.5% by volume of water or higher, but even at lower concentrations, the decrease in value is not significant, especially in drilling fluids that contain mandarin peel powder particles smaller than 0.1 mm.

It is shown that increasing the concentration of mandarin peel powder significantly increases the 10-s gel strength (33% to 75% for drilling fluids with smaller particles than 0.1 mm, and 17% to 108% for drilling fluids with particles between 0.1 and 0.16 mm), while they slightly increase the 10-min gel strength except in the case when mandarin peel powder (particles between 0.1 and 0.16 mm) was added at a concentration of 2% (B4 drilling fluid), and the gel-strength increase amounted to 45%.

Table 11 shows an increase/decrease of pressure loss values relative to values obtained with base drilling fluid, expressed as percentages.

It is shown that a concentration of mandarin peel powder below 1% reduces pressure loss around the drill pipe and drill collar, which corresponds to the results of plastic viscosity and yield point. For laminar flow, by adding smaller particle sizes (up to 0.1 mm) higher pressure losses were calculated for concentrations of 1.5% (26.8%) and 2% (28.4%); meanwhile, for larger tested particles (between 0.1 and 0.16 mm), higher pressure losses were calculated for a concentration of 2% (25.7%). For turbulent flow, only the addition of 2% mandarin peel powder (particles between 0.1 and 0.16 mm) increased pressure loss by 10.5%, while in other cases the impact was negligible.

Table 11. Increase/decrease values of pressure loss values.

Pressure Loss	Increase (+)/Decrease (−) (%)							
	A1	A2	A3	A4	B1	B2	B3	B4
Around drill pipe	−5.1	0.0	26.8	28.4	−25.5	−8.9	1.6	25.7
Around drill collar	0.0	−0.8	1.4	2.5	0.0	1.4	1.4	10.5

Comparing the results with previous research, increases in the values of rheological parameters are somewhat more moderate compared to the results of Al-Hameedi et al. [28], who obtained significant increases of rheological parameters at a lower concentration of 1% (PV increase 100%, YP increase 27%), while gel strength values decreased up to 2% by volume of water, then increased, with the highest values measured at a concentration of 4% by volume of water. Moreover, the API filtration decreased significantly (44%), even at a low concentration of mandarin peel powder (1% by volume of water); meanwhile, in this study a concentration of 4% by volume of water was required to obtain a similar decrease in API filtration. Additionally, it was found that a lower concentration of mandarin peel powder, up to 1.5% by volume of water, is needed to achieve optimal properties.

In general, based on the research results, it can be concluded that by increasing the concentration of mandarin peel powder, rheological parameters increase and filtration decreases. According to Ojha et al. (2016), the solubility of mandarin powder in water is about 28% [48]; thus it can be assumed that the viscosity of the filtrate increases, thereby increasing the resistance to leakage of the filtrate through a drilling fluid cake/ceramic disc, which consequently results in a decrease in filtration value. In addition, plugging of the pores of the drilling fluid cake is likely to occur, and in order to gain better insight, it is necessary to obtain SEM images of the drilling fluid cake to determine the possible mechanisms for the reduction in filtrate loss.

5. Conclusions

Based on laboratory testing, the following conclusions can be drawn:

- Mandarin peel powder particle size and concentration have influence on drilling fluid properties.
- By increasing the mandarin powder concentration, the API filtration decreases.
- PPT filtration significantly decreased by 61.54% and 57.69% with A4 and B4 drilling fluids, respectively.
- Spurt loss significantly decreased by 75% and 37.5% with A4 and B4, respectively.
- By adding mandarin peel powder (particles less than 0.1 mm), rheological parameters generally increase and remain within acceptable limits.
- By adding mandarin peel powder (particles between 0.1 and 0.16 mm), rheological parameters generally increase. At a concentration of 2%, PV and 10-s gel strength values significantly increase, resulting in increased pressure loss.
- Comparing the particle sizes of mandarin peel powder, it can be concluded that slightly better results were obtained with larger particles between 0.1 and 0.16 mm, but for field operations both sizes yield satisfactory drilling fluid properties.
- In general, it can be concluded that the optimal concentration of mandarin peel powder is up to 1.5% by volume of water.

These data provide a good basis for further testing with other food waste which can also be used as an additive to optimize drilling fluid properties. In addition, determining drilling fluid properties in more complex drilling fluid compositions is recommended.

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the introduction section and figures. All authors have read and agreed to the published version of the manuscript.

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