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The Behaviour of Fresh Concrete with Varying Coarse Aggregate Content at the Concrete-Steel Wall Interface

Audrė Rugytė [1], Mindaugas Daukšys [1,*], Svajūnas Juočiūnas [1] and Ruben Paul Borg [2]

[1] Faculty of Civil Engineering and Architecture, Kaunas University of Technology, 44249 Kaunas, Lithuania; raudre@gmail.com (A.R.); svajunas.juociunas@ktu.lt (S.J.)
[2] Faculty for the Built Enviroment, University of Malta, MSD 2080 Msida, Malta; ruben.p.borg@um.edu.mt
* Correspondence: mindaugas.dauksys@ktu.lt

Abstract: The interaction between concrete and steel occurs during concrete mixing and finishing processes, during filling of concrete moulds, formwork, composite columns and during pumping of concrete mixtures. More experimental investigation is required to predict variations in interface friction, as a result of the composition of the lubrication layer which depends on the composition of concrete. This study provides experimental results to allow for a better understanding of friction at concrete-steel interface, with changes in the coarse aggregate (CA) content in the aggregate mixture (AM). Friction tests on fresh concrete have been carried out using the BTRHEOM tribometer (Nantes, France) and the interface parameters were calculated on the basis of the interface friction between the concrete and the steel wall, through the ADRHEO software. The roughness parameters were measured along the length of the rotary steel cylinder of the tribometer. In addition, the roughness of new and modified metal form-lining in steel composite columns was also measured. Variations in the CA content in the AM in the 42 to 52% range had minimal effects on the yield stress of the interface. The viscous constant of the interface as measured with a tribometer decreased, when the roughness parameter *Rt* values of the rotary cylinder wall, which refer to the absolute vertical distance between the maximum profile peak height and the maximum profile valley depth along the sampling length, were in the 17.10 to 28.73 µm range. The roughness profile peaks' asperity recorded, was higher for the worn metal form-lining and for the steel composite columns with the inner surface covered in rust, when compared to the rotary cylinder roughness profile. The hypothesis is based on the principle that a sufficient lubrication layer, with the required thickness of fine mortar is created at the interface between the concrete and the metal form-lining or steel composite column wall, when the CA content in the AM varies in the range from 42 to 52% and the wall roughness parameters (*Rt*) of these elements varies in the 15.00 to 30.00 µm range.

Keywords: coarse aggregate content; lubrication layer; tribometer; yield stress of the interface; viscous constant of the interface; steel surface roughness

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Citation: Rugytė, A.; Daukšys, M.; Juočiūnas, S.; Borg, R.P. The Behaviour of Fresh Concrete with Varying Coarse Aggregate Content at the Concrete-Steel Wall Interface. *Buildings* **2021**, *11*, 2. https://dx.doi.org/10.3390/buildings11010002

Received: 14 October 2020
Accepted: 19 December 2020
Published: 22 December 2020

1. Introduction

Friction at the fresh concrete/steel interface plays an important role during various stages of construction processes. These include concrete mixing and finishing, filling concrete moulds, formwork, and composite columns, and pumping of concrete mixtures, where concrete moves relatively to the surface of the wall. It is important to investigate the relationship between the concrete mix design and the steel wall parameters, in order to reduce variations in friction at the concrete-steel interface. The composition of the lubrication layer at the interface varies with the composition of the concrete mix, in particular with changes in the coarse aggregate (CA) content in the aggregate mixture (AM).

In the case of pumped concrete, fresh concrete moves through the pipe, by sliding over a lubrication layer, consisting of a fine mortar, close to the pipe wall [1–4]. The flowability of fresh concrete during the pumping process depends on the properties of the fine mortar layer, particularly its yield stress (Pa) and the viscous constant (Pa·s/m). Eckardstein [5] provides several practical guidelines on how to reduce or predict problems, which occur in the lubrication layer during the pumping of concrete mixtures through pipes. The properties of the boundary or lubrication layer can be determined when the contribution of concrete shearing to the rotational velocity is known. According to Feys et al. [6] it is important to determine the rheological properties of a concrete mixture through rheological tests, together with the tribological test. In addition, the choice of the rheometer used in the determination of rheological properties, can influence the results obtained with the tribometer. The properties of the boundary or lubrication layer and the roughness of the pipe wall's inner surface have a significant effect on the concrete sliding through the pipes [7]. The concrete mix design can impact the properties of the lubricant layer produced between concrete and the pipe.

The friction at the concrete-steel interface plays an important role and has an effect on the pumpability of the concrete mixture. For a better understanding of concrete behaviour at the concrete/wall interface, various types of "tribometers" have been developed in the last decade. The tribometer is an instrument that measures tribological parameters between two surfaces in contact. Tribometers can be divided into three categories [8], according to the principle of operation: equipment which can provide the pumping process while the fresh concrete slides through a pipe; equipment (so-called rectilinear movement tribometer) which presses fresh concrete samples against a moving steel plate surface and measures the tangential force; equipment which works on the rotary movement principle while concrete is sheared between two coaxial cylinders. The Sliding Pipe Rheometer is also applied to estimate the mixture pumpability. Secrieru et al. [9] determined the correlation between the concrete mixture Bingham model parameters and slippage resistance parameters related to pumpability using the Sliding Pipe Rheometer (SLIPER).

Various authors [10–13] used the rectilinear movement tribometer and investigated the impact of different parameters on the concrete/steel plate friction coefficient. The parameters are as follows: the roughness of the steel plate surface, the sliding velocity of concrete mixture sample against the steel plate, the pressure value, the kind and amount of the release agent at the concrete/steel wall interface. It was concluded that due to the release agent composition it is possible to reduce friction at the concrete/steel interface. During the pouring of concrete demoulding oils have an effect on the friction stress, which depends on the contact pressure and the sliding velocity of concrete. With an increase in the water to cement ratio W/C, interface friction is reduced significantly, together with a decrease in the corresponding viscous constant. The addition of superplasticiser in concrete increases the concrete slump, which reduces the interface friction and the corresponding viscous constant [14]. Djelal [15] reported that the movement of particles in clay-water mixtures depends on the interrelation between the clay particle size and the steel plate roughness amplitude. The measured steel surface value *Ra*, describes the *c* roughness class. Machined steel surfaces with different roughness classes, have different friction features and the surface structure is often closely related to the friction [16].

The behaviour of fresh concrete on the formwork surface depends on the concrete mix proportions, the chemical admixtures used, ambient air temperature during casting, casting rate of concrete and the height of formwork used on the construction site [11,17,18]. Libessart et al. [18] reported that the level of friction at the fresh concrete/formwork surface directly depends on roughness parameters of the formwork used. It was concluded that fines in concrete mixtures have an impact on the lubrication or fine mortar layer close to the formwork surface. Some authors [17,19] noticed that the formwork lateral pressure is influenced by concrete mix proportions, placing temperature of the concrete mixture, the chemical admixtures type and amount used, ambient air temperature, casting rate of concrete and friction at the interface between the fresh concrete and formwork used on the construction site. Kwon et al. [17] proposed a prediction model, which includes the effect of wall friction, formwork flexibility and external temperature, in order to predict variations in formwork pressure over time. Formworks made from different surface materials have different impacts on the lateral pressure of concrete [20]. Watering of timber formwork surfaces before pouring the concrete mixture has an effect not only on changes to the water/cement ratio but also on the friction at the interface between timber formwork and the fresh concrete.

Various studies have shown that the interface friction between concrete and steel occurs at various stages of the construction processes. In addition, friction can be determined by the thickness and the rheology of the lubrication layer formed at the interface between the concrete and steel; the roughness of the steel surface has an influence on the friction of the lubrication layer at the interface. Various tribometers are used to determine the relationship between the concrete composition parameters and the interface friction. Friction exerted by concrete on metal surfaces plays an important role during placing operations, especially when the surface of the formwork is not covered by demoulding oils to reduce the interface friction at the concrete-steel interface. This is also the case of steel composite columns with different surface roughness parameters. The surface irregularities of steel composite columns are created through machining. In the case of steel composite columns, the relationship between the concrete composition parameters and the interface friction of the steel needs to be determined. The objective of the research presented in this article is to analyse the effects of coarse aggregate (CA) content in the aggregate mixture (AM) and variations in the composition of the lubrication layer on the friction at the concrete-steel wall interface.

2. Materials and Methods

Portland cement CEM I 42.5 R sourced from JSC "Akmenės cementas" in Lithuania was used as binder satisfying the requirements set out in LST EN 197-1 [21]. The physical properties of the cement were as follows: specific surface area by Blaine apparatus 410 m^2/kg, particle density 3050 kg/m^3, dry bulk density 1210 kg/m^3 and water demand for standard consistency by Vicat 26.5%.

The fine aggregates used in the research consisted of sand sourced from "Kvesu" quarry (JSC "Kvesų karjeras", Lithuania) with sizes as follows: 0–1 mm and 0–4 mm. The physical properties of the sands were as follows: dry bulk density 1521 kg/m^3 and 1711 kg/m^3, specific gravity of both at about 2.66, water absorption 0.56% and 0.50% respectively. Sand of size 0–1 mm with fineness modulus of 2.3 was defined as fine sand and sand of size 0–4 mm with fineness modulus of 3.2 was defined as coarse sand.

Gravel of size 4–16 mm and with dry bulk density 1457 kg/m^3, specific gravity 2.67 and water absorption 1.39%, was used as coarse aggregate. The flakiness index of the gravel of size 4–16 mm was 4%. This index describes the percentage by weight of aggregate particles whose least dimension is less than 0.6 of their mean dimensions. Aggregate particles with a nearly spherical shape and a smooth surface texture were used in this research. The granulometric properties of the aggregate used were determined in accordance to the standard LST EN 12620 [22] and presented in Table 1.

Table 1. Sieve analysis data of the aggregates.

Sieve Size, mm	Passing (%)		
	Sand in Fracture 0–1 mm	Sand in Fracture 0–4 mm	Gravel in Fracture 4–16 mm
31.5	-	-	100.0
16.0	-	-	93.0
8.0	-	100.0	25.4
4.0	100.0	97.5	0.4
2.0	99.9	87.7	0.0
1.0	98.1	71.9	0.0
0.500	92.5	56.0	0.0
0.250	28.0	17.4	0.0
0.125	3.2	4.6	0.0
0	0.0	0.0	0.0

Glenium SKY 628 supplied by BASF Constructions Chemicals (Spa, Italia), based on polycarboxylic ether polymers was used as plasticising admixture. The superplasticiser consists in a yellow liquid with a density of 1.06 kg/L and 1.0% of superplasticiser by weight of cement was added to the concrete.

In the research, 6 different concrete mix compositions were considered. For each mixture composition two samples were made and tested. The concrete mix designs with an amount of material (kg) per cu. m. of concrete are presented in Table 2.

Table 2. Composition and technological properties of tested mixture series.

Marking	The Amount of Materials per cu. m. of Concrete Mixture (kg)							Technological Properties		
	Content of CA (%)	Portland Cement	Gravel Fraction 4/16	Sand Fraction 0/4	Sand Fraction 0/1	Water	Super-Plasticizer	Slump Value (mm)	Density (kg/m^3)	Air Content (%)
CM22	22	330	417	986	492	178	3.3	30	2180	7.9
CM32	32	330	607	860	429	178	3.3	50	2160	7.9
CM37	37	330	702	797	397	178	3.3	160	2340	3.9
CM42	42	330	796	733	366	178	3.3	170	2290	5.9
CM47	47	330	891	671	334	178	3.3	190	2380	2.1
CM52	52	330	986	607	303	178	3.3	230	2400	1.6

The content of CA is calculated as a percentage of the total aggregate mixture (AM) by mass. The water to cement ratio (W/C) and plasticising admixture content were constant in all the concrete mixtures. The mixes are based on a constant plasticizing admixture dosage rather than a constant slump. The innovation in the research refers to the effect of total aggregate mixture on the tribological parameters, when the CA content is increased and fine aggregate (FA) content is decreased. All mix compositions were prepared using a sand fraction 0/1, with an increase in the specific surface of fine aggregate in order to retain the mix cohesion. With an AM based on gravel fraction 4/16 (uncrushed aggregate) content above 52% and sand fraction 0/4 and 0/1 content below 48%, the concrete mixture lost cohesion and started to bleed.

The particle size distribution of the final aggregate mixtures (AM), for all the six mixture series analysed with the CA content in the AM changing from 22 to 52%, are presented in Figure 1.

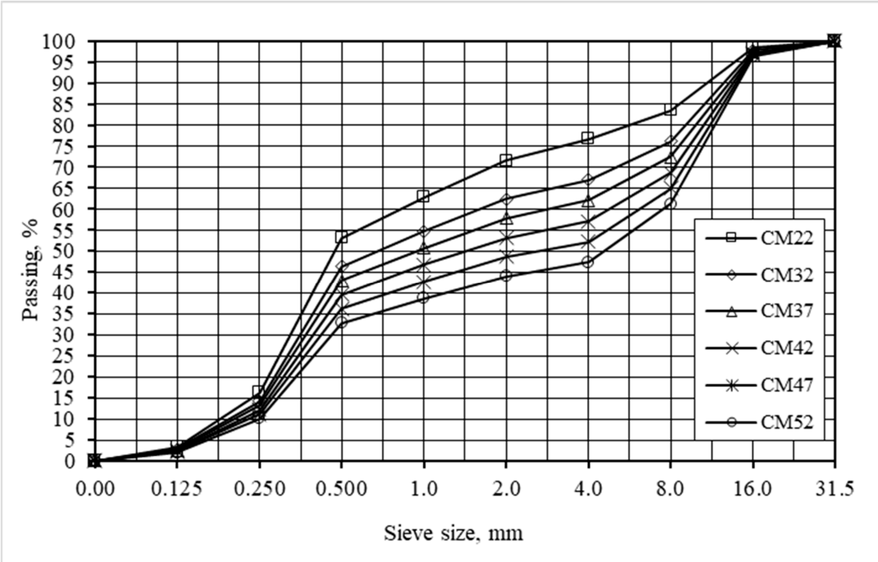


Figure 1. The final aggregate mixture (AM) granulometric composition, when the CA content in the AM changes from 22 to 52%.

Concrete was mixed in accordance to LST EN 206 [23] using dry materials. The concrete mixtures were prepared in the laboratory using a forced type Pemat Mischtechnik GmbH (Freisbach, Germany). The process of mixing was divided in two stages. First, the Portland cement, fine and coarse aggregates and 2/3 of the water were mixed for about 2 min. At a second stage, the remaining amount of water was added and the fresh concrete was mixed for 1 min.

The slump of fresh concrete was determined in accordance to the standard LST EN 12350-2 [24], the density of the fresh concrete in accordance to LST EN 12350-6 [25] and air content of the compacted fresh concrete in accordance to LST EN 12350-7 [26].

The rheological behaviour of ordinary concrete can be described with reference to the Bingham model fluids and with reference to the main rheological properties–yield stress (τ_0) and viscosity (η) [8,27,28]. The Bingham model is described in Equation (1):

$$\tau = \tau_0 + \eta \cdot \gamma \tag{1}$$

Here: τ—the shear stress of concrete, Pa; τ_0—the yield stress of concrete, Pa; η—the viscosity of concrete, Pa·s and γ—the share rate, 1/s.

The technological properties of the concrete mixture are related to its rheological properties and therefore it is easier to establish the yield stress of the concrete from its slump and density. The yield stress of concrete mixtures was evaluated using Equation (2), and was also adopted by other authors in their research [29–32]:

$$\tau_0 = \frac{0.00815 \cdot \rho_m}{\left(\sqrt{\frac{0.498}{30-SL}} - 0.001724 - 0.024\right)^2} \tag{2}$$

Here: ρ_m density of the concrete mixture, kg/m^3; SL—the slump of the concrete mixture, cm.

The plastic viscosity of the concrete mixture was evaluated using Equation (3), which was also adopted by other authors in their research [28,29,31,32]:

$$\eta = \eta_w \cdot exp\left[\frac{a_c \cdot \rho_w}{\rho_w \cdot \frac{W}{C} \cdot \rho_c - b_c \cdot \rho_w} + \frac{a_{fa(1-\varphi_{ca}-\varphi_{ea}-\frac{W}{\rho_w}-\frac{C}{\rho_c})}}{1-\varphi_{ca}-b_{fa}\left(1-\varphi_{ca}-\varphi_{ea}-\frac{W}{\rho_w}-\frac{C}{\rho_c}\right)} + \frac{a_{ca}+\varphi_{ca}}{1-b_{ca}-\varphi_{ca}}\right] \cdot K_{adm} \tag{3}$$

Here: η_w—the viscosity of water, Pa·s; φ_{ea}—the amount of entrapped air in fresh concrete, %; W, C—the content of water and cement in concrete mixture (the amount of materials per m^3), kg; ρ_w, ρ_c—the densities value of water and cement, kg/m^3; φ_{ca}—the volume concentration of gravel (4/16 fraction) in concrete mixture; a_c, a_{fa}, a_c—the form of cement, sand (0/1 and 0/4 fraction) and gravel (4/16 fraction) particles describing factors (a_c = 2.6; a_{fa} = 2.5; a_{ca} = 2.6) according to their angularity; b_c, b_{fa}, b_{ca}—the density distribution of cement (b_c = 1.287), sand of size 0–1 mm (b_{fa} = 1.193 ÷ 1.226), sand of size 0–4 mm (b_{fa} = 1.236 ÷ 1.212) and gravel of size 4/16 mm (b_{ca} = 1.236) describing factors in cement paste, mortar and concrete mixture respectively. The coefficient of correction K_{adm} describes the influence of the admixture on the plastic viscosity of the concrete mixture. The coefficient was calculated as a ratio of cement paste viscosity values obtained without and with admixtures. For superplastisicer based on polycarboxylic ether polymers, it was equal to 0.085.

In this study, the relationship between the interface parameters and the interface friction, was analysed using the BTRHEOM tribometer (Figure 2). Several authors have validated this kind of tribometer through their research [33–36]. A fifteen-litre concrete sample is placed in the hollow cylindrical container, and is sheared between two coaxial cylinders. The internal cylinder is rotated at different speeds.

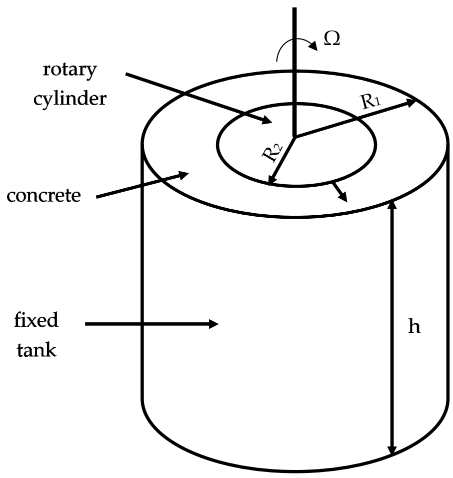


Figure 2. Principal working scheme of BTRHEOM tribometer.

The behaviour of the concrete-steel wall interface is described through the following model in Equation (4) [11]:

$$\tau = \tau_{0i} + \eta_i \cdot V \tag{4}$$

where: τ—the shear stress of the interface, Pa; τ_{0i}—the yield stress of the interface, Pa; η_i—the viscous constant of the interface, Pa·s/m and V—the relative velocity of slip, m/s.

The raw output of the test appears as a torque–rotation speed diagram. Two scenarios can be assessed: (a) the sample is kept still during the test and shearing is localised at the concrete-steel interface, (b) the rotation velocity is high enough, so that a part of the concrete begins to be sheared. An equation linking the torque and the rotation speed corresponds to each of these scenarios. These rheological properties refer to the concrete type for the scenario, which are obtained at the time of testing. The tribological parameters (the yield stress and the viscous constant of the interface) were calculated from the raw experimental data (torque–rotation speed diagram) using ADRHEO software. The tribometer used has the following characteristics: fixed tank with an internal diameter of 350 mm and 200 mm height; rotary cylinder with 150 mm diameter and 200 mm height; mass of the device 7.9 kg; precision of measured data: yield stress of the interface about ±18% and viscous constant of the interface about ±7% (with a confidence level of 95% for the two parameters).

The surface roughness parameters of the rotary steel cylinder, steel column formworks and steel composite columns were determined using a roughness gauge, the Tesa Rugosurf 20. The Rugosurf software displays surface roughness profile, bearing area curve (Abbott) and the basic parameters of roughness: arithmetical mean height value (*Ra*), which indicates the average of the absolute value along the sampling length; root mean square deviation value (*Rq*), which indicates the root mean square along the sampling length; maximum height value (*Rt*) of the profile, which indicates the absolute vertical distance between the maximum profile peak height and the maximum profile valley depth along the sampling length; mean height value (*Rc*) of profile elements, which indicates the average value of the height of the curved element along the sampling length. Surface roughness measurement methods include the linear roughness measurement, which consists of a measurement of a single line on the sample surface. The main component of the equipment is a measuring tip with a diamond needle (with a tip radius of 5 μm). This needle is held in contact with the tested surface and pulled in one direction, registering all irregularities of the tested surface through a vertical movement with respect to the test surface. The maximum vertical movement distance is 400 μm and the surface irregularity recording resolution is 0.001 μm. A single measurement length is 12.5 mm (2.5 mm × 5). Surface roughness was determined in accordance to LST EN ISO 4287 [37].

3. Results and Discussion

3.1. Effect of Coarse Aggregate Content on Concrete-Steel Wall Interface.

The technological properties of the tested concrete mixture series are presented in Table 2. We can see that with the change of CA content (gravel 4–16 mm) from 22 to 52%, the slump value of the fresh concrete mixtures increased from 30 to 230 mm; the air content in fresh concrete mixtures decreased from 7.9 to 1.6% and the density values of fresh concrete increased from 2180 to 2400 kg/m^3. While the CA content in the AM increased, the content of sand decreased accordingly.

With an increase in the CA content and decreasing fine aggregate (FA—sand fraction 0/4 and 0/1) content in the AM, the surface area of the aggregate particles decreases. This means that to coat the surface of the aggregate, less cement paste is needed and as a result the workability of the concrete mixture increases due to the extra cement paste in the mix. The extra content of cement paste increases the slump of the concrete mixtures. The entrapped air content in fresh concrete and density of fresh concrete mixtures depend on the distribution density and surface area of the solid particles in the concrete mixtures [38]. By increasing the CA content in the constant AM volume, the air content in the cement paste decreases. This has an effect on the increment of air content and on the reduction in density of the tested concrete mixture series.

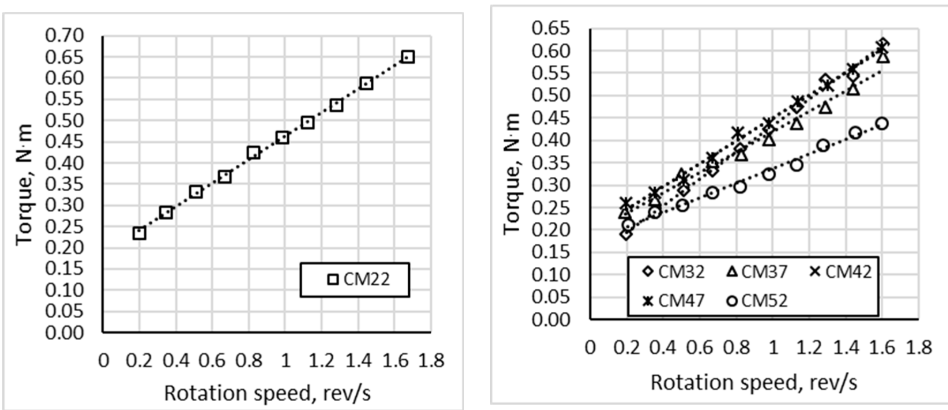
The measurement of the interface friction between the concrete and the rotary steel cylinder using the tribometer allows for the determination of the interface parameters. Before testing of the concrete-steel wall interface parameters using the BTRHEOM tribometer, input data are required for the rheological properties of the fresh concrete mixtures. The yield stress and viscosity of the mixtures were determined with reference to equations Equations (2) and (3). Results are given in Table 3.

Changes in the CA content in the AM affect the yield stress and viscosity of the fresh concrete. When the content of gravel fraction 4/16 in the AM increases from 22 to 52% (the FA content decreases from 78 to 48%), the yield stress and the viscosity of the mixture decrease. Therefore the water and cement paste content requirements for concrete change, due to changes in the specific surface of the CA. Water and cement quantities during concrete preparation are constant. Due to the reduced surface area of FA particles, CA particles require less paste to reach a given consistency. When less cement paste is required to fill the space between CA particles, the extra cement paste reduces the friction between aggregates. Particles with a nearly spherical shape and a smooth surface texture contribute to less friction between the coarse aggregate and result in a more workable concrete as reported by Kurokawa et al. [39]. It means that these factors contribute towards a decrease in the yield stress and viscosity (Table 3). Hu and Wang [40] have shown that larger size aggregate generally results in concrete with lower yield stress and viscosity.

Table 3. Rheological and tribological properties for tested concrete mixtures series.

Marking	Calculated Input Data		Output Data from the Tribometer					
			First Series			Second Series		
	Yield Stress (Pa)	Viscosity (Pa·s)	Coefficient of Correlation (r)	Yield Stress of the Interface (Pa)	Viscous Constant of the Interface (Pa·s/m)	Coefficient of Correlation (r)	Yield Stress of the Interface (Pa)	Viscous Constant of the Interface (Pa·s/m)
CM22	727	54.84	0.9951	28	44	0.9994	26	41
CM32	621	8.47	0.9976	19	45	0.9969	21	43
CM37	520	3.00	0.9923	28	34	0.9794	30	28
CM42	476	3.46	0.9969	28	38	0.9904	29	32
CM47	350	2.00	0.9950	25	28	0.9708	35	18
CM52	292	2.14	0.9960	25	24	0.9951	29	18

The calculated rheological properties were used as input data for the determination of the interface friction using tribometer. Figure 3 presents the evolution of the torques with the rotational speed, while the CA content in the AM changes from 22 to 52%. The curves represent the data of the series with a higher correlation coefficient value through linear regression analysis (Table 3). With the increase in rotation speeds the torques corresponding to different content of CA in the AM, increases linearly. The decrease in the slopes of the torque-speed curves (from 21° to 7°) demonstrate that the interface friction decreases when the CA content in the AM increases. This allows for an improvement of the properties of the lubrication layer at the concrete-steel interface. The interface friction corresponding to the CA content in AM of 52% is the lowest, when compared to those of the other tested concrete mix compositions.



(**a**) (**b**)

Figure 3. Evolution of the torque with the rotation speed while the CA content in the AM changes from 22 to 52%: (**a**) partial shearing of the concrete, (**b**) shearing was localised at the concrete steel interface.

During the testing stage, two scenarios were observed with respect to the shearing zone (Figure 4): (a) the rotation velocity was high enough, resulting in partial shearing of the concrete mix with 22% CA content in the AM (b) the concrete mix sample with a CA content in the AM of 32–52%, was kept still during the test and shearing was localised at the concrete-steel interface. Due to partial shearing of the concrete (Figure 4a), the concrete mix with the CA content in the AM of 22% does not have an impact on lubrication layer and was not used any further for comparisons.

Figure 4. The scenarios observed during testing: (**a**) partial shearing of concrete, (**b**) shearing was localised at the concrete steel interface.

The yield stress and the viscous constant of the interface values from the torques-rotation speed diagram, were calculated using the ADRHEO software, during testing. Results are presented in Table 3 and Figure 5. The yield stress and viscous constant of the interface describe properties of the lubrication layer. When concrete is being tested using the tribometer, the lubrication layer is formed at the interface between the concrete mix and the rotary cylinder wall. The flow of fresh concrete close to the wall depends on the lubrication layer properties and the wall surface roughness parameters. The relationship between the yield stress of the interface and the yield stress of concrete when the CA content in the AM changes from 32 to 52% is presented in Figure 4. It can be noted that changes in the CA content in the AM from 32 to 52%, have minimal effects on the yield stress of the interface, while the yield stress of concrete is decreasing significantly.

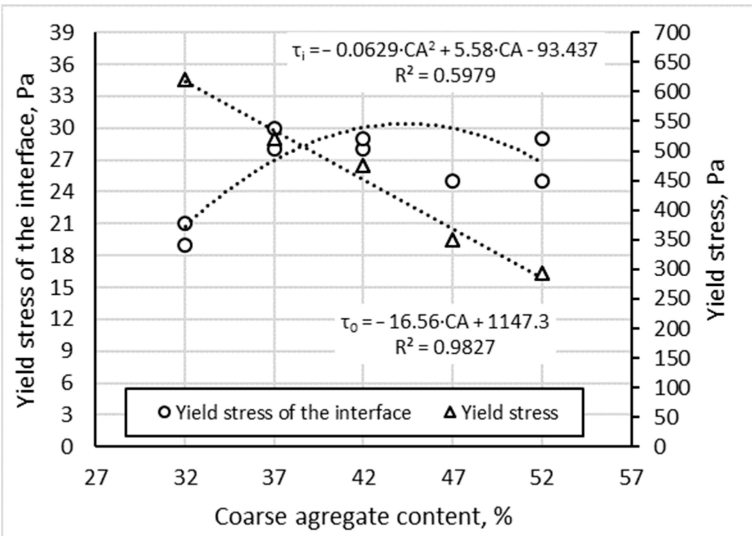


Figure 5. Relationship between the yield stress of the interface and the yield stress, when the CA content in the AM changes from 32 to 52%.

Variations in the yield stress of the interface with respect to the fresh concrete slump are presented in Figure 6. Results show that the increase in the CA content in the AM from 32 to 52% results in an increase in concrete slump and has minimal effect on the yield stress of the interface.

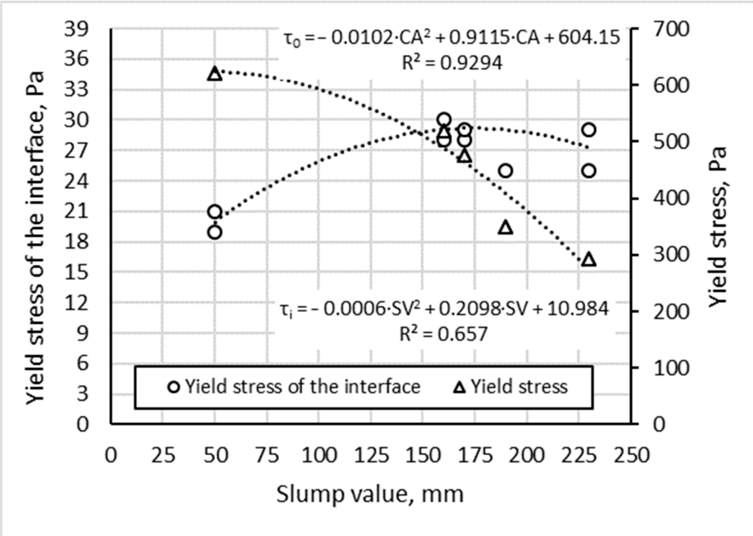


Figure 6. Relationship between yield stress of the interface and the yield stress, when consistency in the slump changes from 50 to 230 mm.

Figure 5 shows that in the curve there is a point, at 42% of CA content in the AM, with the yield stress of the interface values decreasing on either side. The yield stress of the interface increases slightly with an increase in the CA content in AM from 32 to 42% until this point is reached. After that the yield stress of the interface decreases slightly with an increase in the CA content in AM from 42 to 52%. Figure 6 shows there is also a point at 170 mm (Table 2), the slump value, when the CA content in the AM is about 42%, for which the yield stress of the interface values decreases on either side. It can be noted that changes in the CA content in the AM from 32 to 52% are not sufficient to contribute significantly on the yield stress of the interface.

The relationship between the viscous constant of the interface and the viscosity of concrete when the CA content in the AM changes from 32 to 52% is presented in Figure 7. It can be noted that an increase in CA content in the AM from 32 to 52% slightly decreases the viscous constant of the interface and significantly decreases the viscosity of fresh concrete.

Changes in the CA content in the AM affect the yield stress and viscosity of the fresh concrete. When the content of gravel fraction 4/16 in the AM increases from 22 to 52% (the FA content decreases from 78 to 48%), the yield stress and the viscosity of the mixture decrease. Therefore the water and cement paste content requirements for concrete change, due to changes in the specific surface of the CA. Water and cement quantities during concrete preparation are constant. Due to the reduced surface area of FA particles, CA particles require less paste to reach a given consistency. When less cement paste is required to fill the space between CA particles, the extra cement paste reduces the friction between aggregates. Particles with a nearly spherical shape and a smooth surface texture contribute to less friction between the coarse aggregate and result in a more workable concrete as reported by Kurokawa et al. [39]. It means that these factors contribute towards a decrease in the yield stress and viscosity (Table 3). Hu and Wang [40] have shown that larger size aggregate generally results in concrete with lower yield stress and viscosity.

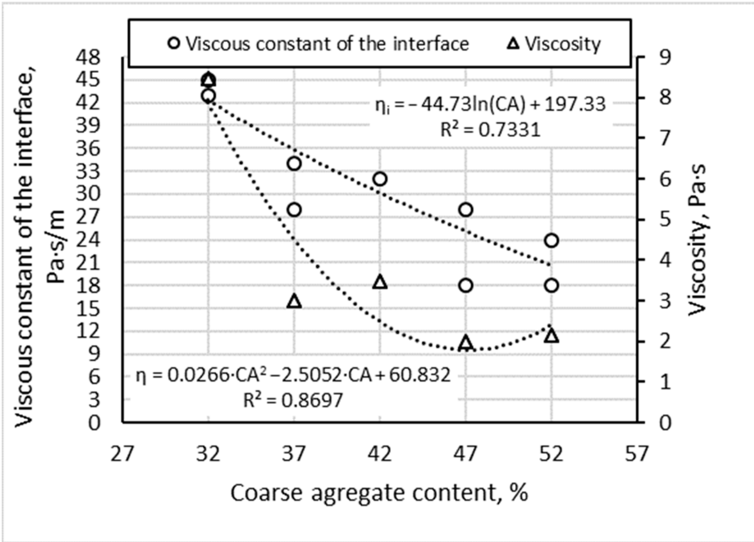


Figure 7. Relationship between the viscous constant of the interface and the viscosity of concrete, when the CA content in the AM changes from 32 to 52%.

The influence of CA content in the AM on the concrete-steel wall interface parameters using the tribometer showed that changes of the CA content in the AM from 42 to 52% had minimal effects on the yield stress of the interface and resulted in a decrease in the viscous constant of the interface while slump values varied in the range from 170 to 230 mm. It means that the CA content in the AM from 42 to 52% is practical to reduce interface friction at the steel-concrete interface due to variations in the composition of the lubrication layer.

3.2. Effect of Surface Roughness Parameters on Concrete–Steel Wall Interface

The surface roughness analysis of the rotary cylinder is required, in order to investigate the interface friction between the concrete and the wall of the cylinder. A portable roughness gauge Tesa Rugosurf 20 was used for the measurement of roughness along the length of the rotary steel cylinder of the tribometer. In addition, measurements were performed at three different locations, by rotating the cylinder at 120 degrees. The arithmetical mean height value (*Ra*) of the vertical deviation, from the mean line through the profile, varied in the range from 2.36 to 2.97 μm and the distance between the highest asperities and the lowest valleys (*Rt*) through the profile varied in the range from 17.10 to 28.74 μm. It can be noted that the profile is homogeneous. The basic roughness parameters and roughness profiles are presented in Table 4, with respect to three measurements.

In order to compare the known roughness parameters of the rotary cylinder to the roughness parameters of the chosen metal form-lining and steel composite column, additional measurements were performed. Worn metal form-lining and new metal form-lining were analysed in order to understand the effect of the friction process on the evolution of surface roughness. The metal form-lining is used as column formwork in construction. The surface irregularities of the worn metal form-lining are formed by the concrete mixture friction process at the concrete-steel wall interface. The mentioned surface irregularities depend on the number of repeated uses of the metal form-linings for concrete on construction sites. The wearing of metal form-lining was due to friction when casting the concrete, to outdoor storage, to transporting, to lifting, to cleaning. Samples of formwork were provided by the supplier of formwork and scaffolding in Lithuania UAB "Peri Lietuva". The measurement of formwork surface roughness parameters of the new and worn metal form-lining were performed at KTU laboratory. Cold welded steel tubes having different diameters and inner surface roughness were analysed. The surface irregularities of the steel tubes are created through machining and sandblasting process. Measurements of composite steel column surface roughness parameters were performed at the steel construction plant UAB "Peikko Lietuva" as presented in Figure 8 and the measured steel surface roughness parameters are presented in Table 4.

Table 4. Measured steel surface roughness parameters.

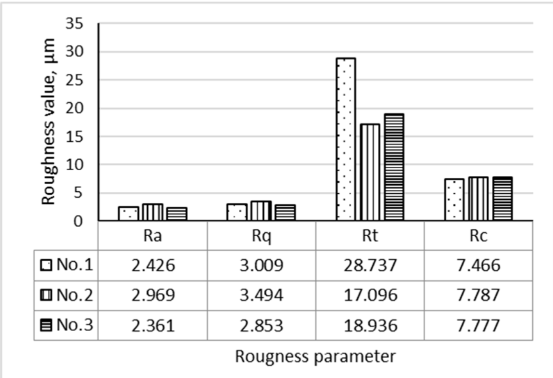
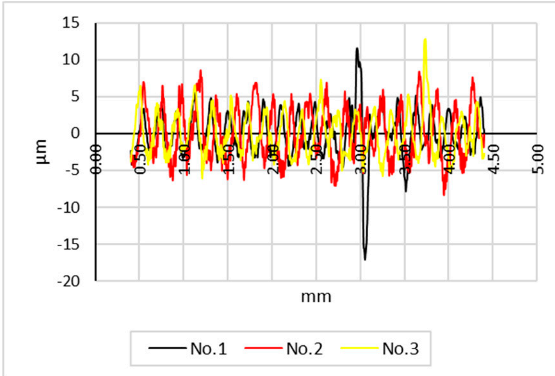
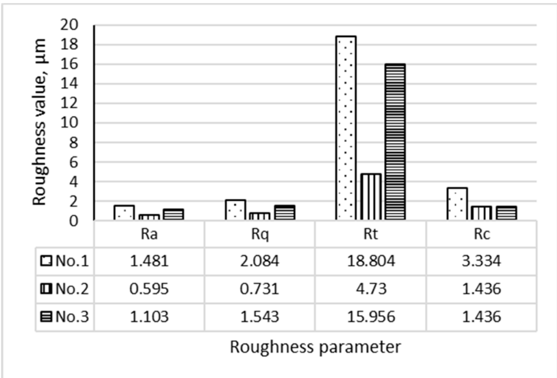
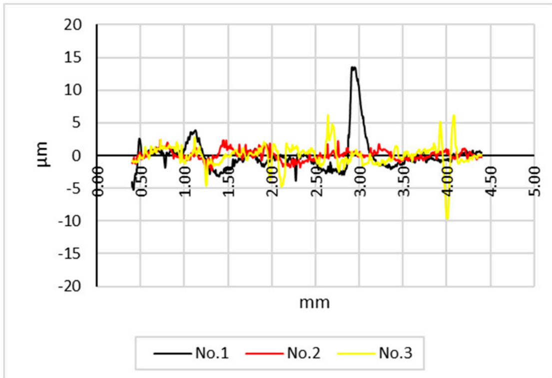
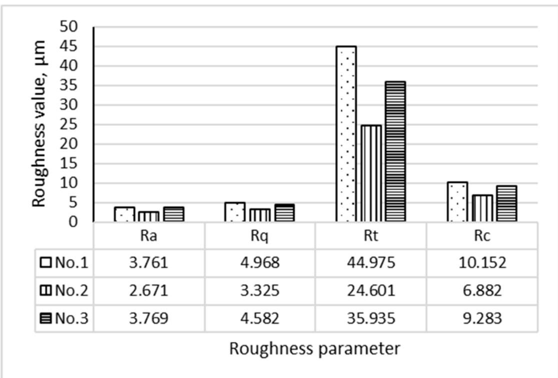
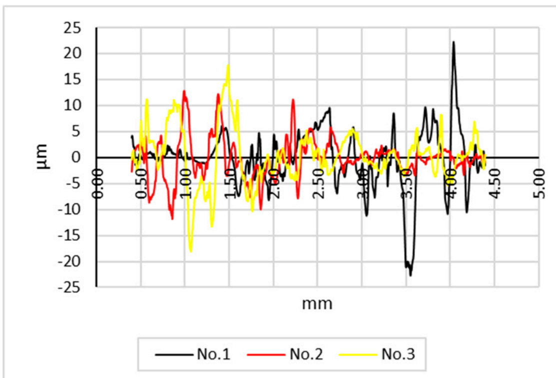
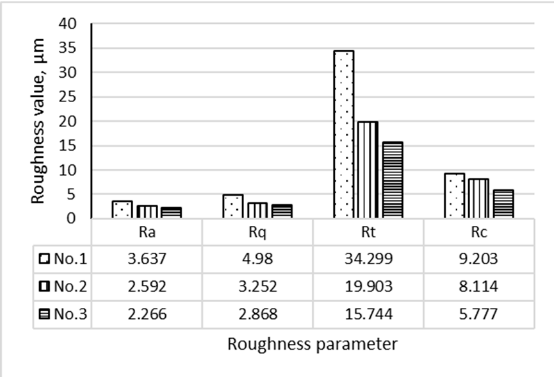
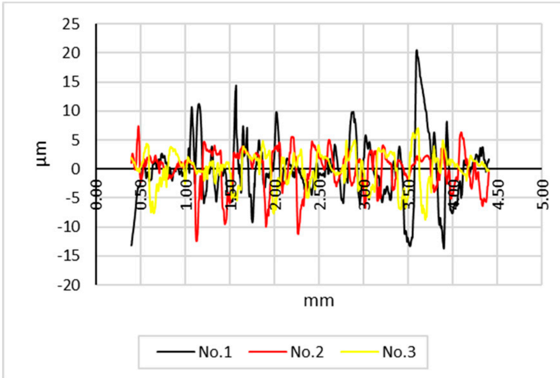
<table>
<tr><th>The Basic Parameters of Roughness</th><th>Roughness Profile</th></tr>
<tr><td colspan="2">Rotary Steel Cylinder</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">New Metal Form-Lining</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Worn Metal Form-Lining</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

Table 4. *Cont.*

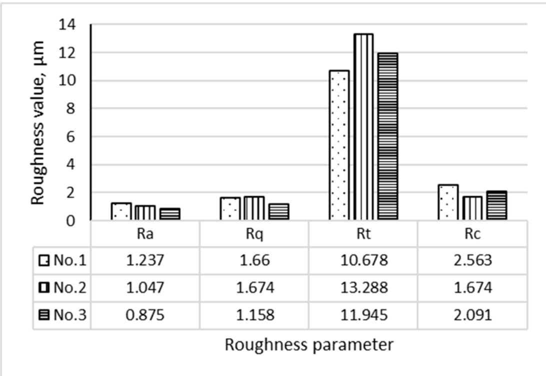
The Basic Parameters of Roughness	Roughness Profile

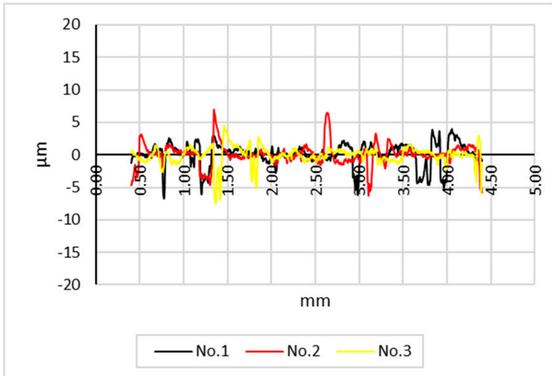
Steel Composite Column No.1



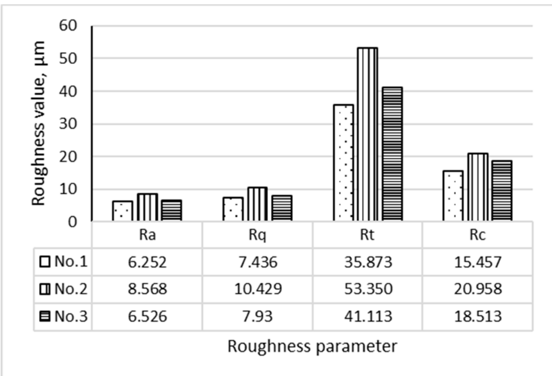


Steel Composite Column No.2





Steel Composite Column No.3



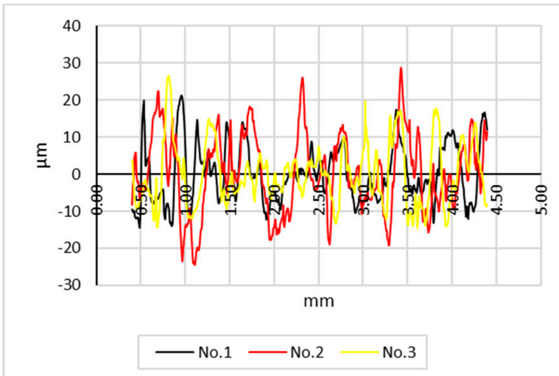
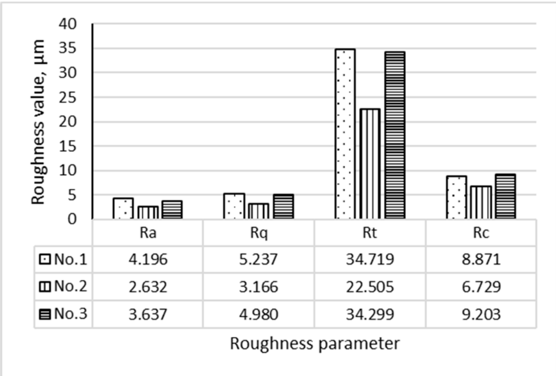
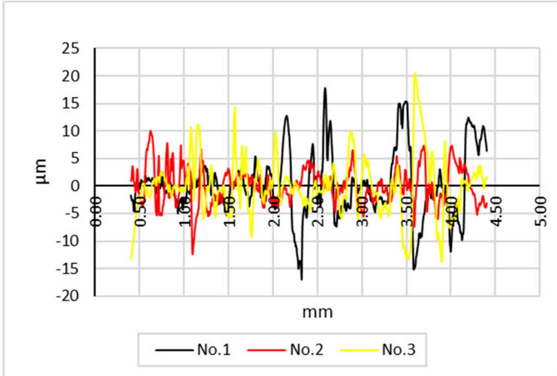


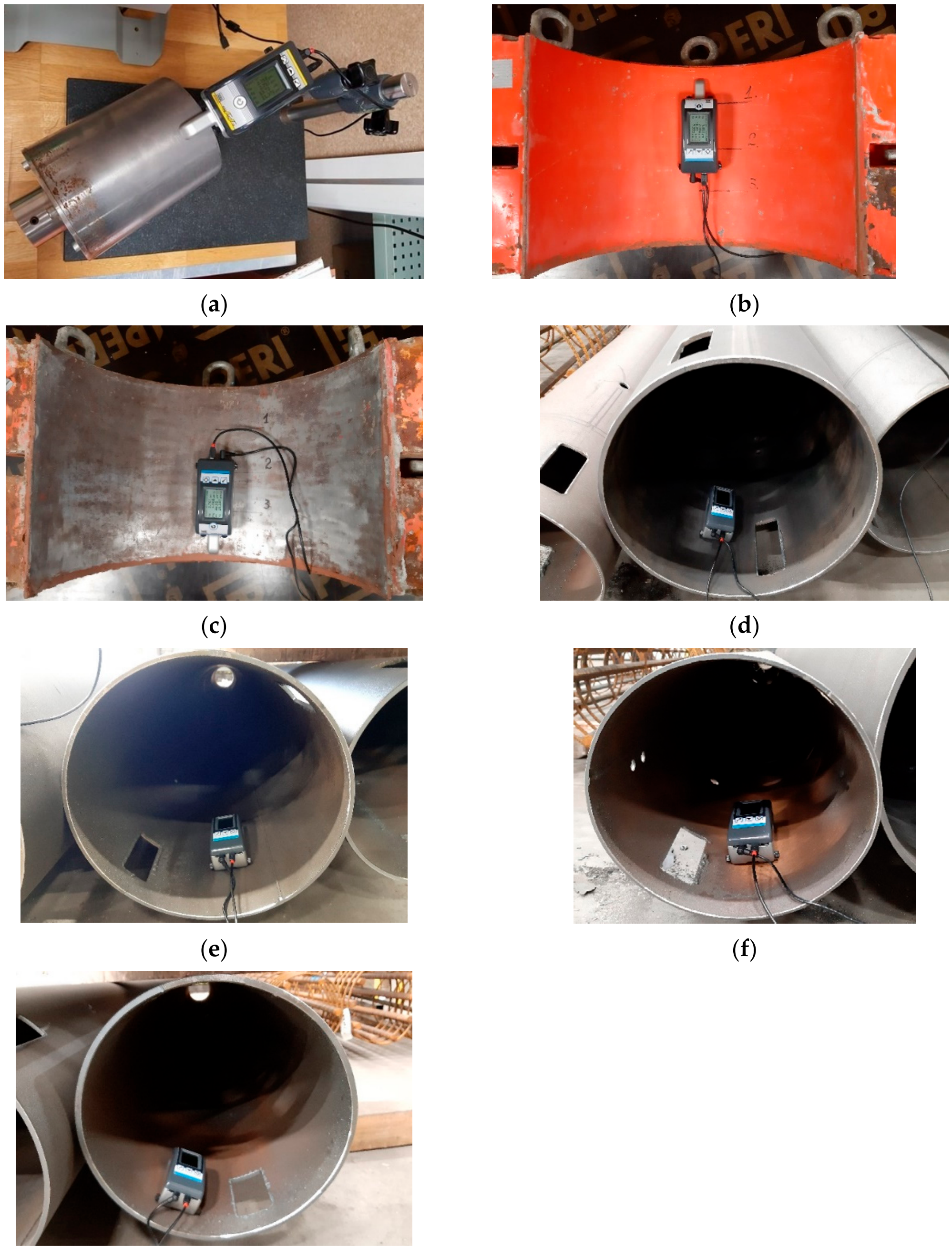
Table 4. *Cont.*

<table>
<tr><th>The Basic Parameters of Roughness</th><th>Roughness Profile</th></tr>
<tr><td colspan="2">Steel Composite Column No.4</td></tr>
<tr><td>
</td><td>
</td></tr>
</table>

The roughness profiles and basic roughness parameters of new and worn metal form-lining and of different types of composite columns (No.1–No.4) are presented in Table 4. When comparing the results of metal form-lining surface roughness, it is noted that the *Rt* values of the used metal form-lining varied in the range from 24.60 to 44.98 µm and are higher than the *Rt* values (from 4.73 to 18.80 µm) recorded for new metal form-lining, while the *Rt* values of the rotary cylinder wall varied in the range from 17.10 to 28.74 µm. When comparing the results of the steel composite columns' surface roughness, it is noted that *Ra* values ranging from 0.88 to 8.57 µm and *Rt* values ranging from 11.95 to 53.35 µm were determined. As expected, asperities peaks of the obtained roughness profile (*Rt*) are higher for the worn metal form-lining and for the steel columns with inner surface which was in part covered in rust (steel composite column No. 3). Kubiak and Mathia [43] concluded, that initial surface roughness can have significant influence on friction and wear processes in tribological contacts under fretting conditions. The degradation of material during the friction process rapidly changes the roughness in tribological contact. After an initial period of rapid degradation, the condition of the interface will stabilise and the increase in roughness is much slower [44]. The wall wearing process depends on such parameters as production flow rate, entrained solid rate in the production fluid, fluid properties, flow regime, solid particle properties, particle geometry, and wall material of the equipment and geometry of the equipment [45].

The influence of CA content in the AM on the concrete-steel wall interface parameters using the tribometer, when roughness *Rt* values of the steel rotary cylinder varied in the range from 17.10 to 28.74 µm, showed that changes of the CA content in the AM from 42 to 52% had minimal effects on the yield stress of the interface and resulted in a decrease in the viscous constant of the interface. The comparison of surface roughness between steel rotary cylinder, metal form-lining and different types of steel composite columns showed that the maximum profile peak height and the maximum profile valley depth along the sampling length (*Rt*) values varied in approximately the same range–15.00 to 30.00 µm, except for the worn metal form-lining and the steel tubes with inner surface which were in part covered in rust, where the determined *Rt* values are higher. It can be noted that the CA content in AM and the wall roughness result in a decrease in the interface friction for the tested concrete mixtures. The hypothesis is based on the principle that a sufficient lubrication layer can be created with the required thickness of fine mortar at the interface between the concrete and the metal form-lining or steel composite column walls, when the CA content in the AM varies in the range from 42 to 52% and the wall roughness parameters (*Rt*) of these elements varies in the range from 15.00 to 30.00 µm. This is especially relevant for the metal form-lining or steel composite columns, when formworks are filled using concrete on site. The concrete moves through the steel surface of such elements, by flowing over a lubrication layer of fine mortar, which forms close to the wall of the relevant element. Surface roughness can influence the level of concrete friction on the surface of the metal form-lining or the composite column, requiring further assessment. Due to the roughness of the relevant element surfaces, the contact between two solids, i.e., concrete mix constituents and the steel wall, takes place first on asperity peaks. The *Rt* value of the profile indicates the absolute vertical distance between the maximum profile peak height and the maximum profile valley depth along the sampling length. It is important to know the value of parameter *Rt* for determining whether the constituent concrete grains are in fact capable of lodging inside the slight asperities [46]. When the concrete mix constituents or grains lodge in the slight asperities, the friction at the concrete-steel interface changes. With the increase in the CA content there is a decrease in FA in AM. Due to a lack of FA particles in the AM there is a decrease in the specific surface of the FA and a lower content of cement paste is needed to coat the coarse aggregate particles. The extra content of cement paste should have a positive effect on the reduction in interface friction between concrete and the steel wall, with cement paste particles lodging inside the slight asperities. Such grains are mainly found in cement and fine sand. It was noticed that the worn metal form-lining and the steel composite column with the inner surface that was in part covered in rust have higher *Rt* values. This means that in such conditions not only cement paste particles but also fine sand particles can be lodging inside the asperities.

When proportioning concrete mixes and determining the mix composition, the rheological and tribological parameters can be controlled. Due to the growth of the ratio of cement paste volume to total aggregate volume, including fine and coarse aggregate, and the rheologically effective amount of water, the required values of the lubrication layer which are necessary for effective decrease of interface friction in the case of different surface conditions can be determined. On the basis of the research results, the hypothesis is based on the principle that a sufficient lubrication layer will be created with the required thickness of fine mortar at the interface between the concrete and the wall of metal form-lining or steel composite column, when the CA content in the AM varies in the range from 42 and 52% and the wall roughness parameters (*Rt*) of these elements varied in the range from 15.00 to 30.00 μm. It allows for the prediction of the interface friction variation through the changes in the lubrication layer composition with variation in concrete mix proportions.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**) (**g**)

Figure 8. Measurement of roughness: rotary steel cylinder (**a**), new metal form-lining (**b**), used metal form-lining (**c**), steel composite column No.1 (**d**), steel composite column No.2 (**e**), steel composite column No.3 (**f**), steel composite column No.4 (**g**).

4. Conclusions

According to the results of this experimental investigation, various key observations can be made with reference to the influence of CA content on the concrete-steel wall interface parameters using the tribometer. The following main conclusions were drawn:

1. Changes of the CA content in the AM from 42 to 52% had minimal effect on the yield stress of the interface and a decrease in the viscous constant of the interface as measured with a tribometer, when *Rt* values of the rotary cylinder wall were in the range from 17.10 to 28.74 µm. Changes of the CA content in the AM from 42 to

52% decrease the viscosity of concrete, while the yield stress of concrete decreased significantly as calculated with the chosen equations.

2. The comparison of surface roughness between steel rotary cylinder, metal form-lining and different types of steel composite columns showed that the maximum profile peak height and the maximum profile valley depth along the sampling length (*Rt*) values varied in the approximately the same range from 15.00 to 30.00 µm, except for worn metal form-lining and the steel tubes with inner surface which was in part covered in rust, where the *Rt* values determined were higher. The value of parameter *Rt* allows for the determination of whether the constituent concrete grains such as cement particle and fine sand particle are in fact capable of lodging inside the asperities and therefore reducing interface friction at the concrete-steel interface.
3. On the basis of the research results, the hypothesis is based on the principle that a sufficient lubrication layer can be created with the required thickness of fine mortar at the interface between the concrete and the metal form-lining or steel composite column wall, when the CA content in the AM varies in the range from 42 to 52% and the wall roughness parameters (*Rt*) of these elements varies in the range from 15.00 to 30.00 µm. It allows the prediction of the interface friction variation, with changes in the lubrication layer as a result of variations in the concrete mix composition.

This research based on an experimental investigation provides for an understanding of interface friction at the concrete-steel walls, with variations in the coarse aggregate (CA) content in the aggregate mixture (AM) in concrete mixes.

Author Contributions: Conceptualization, A.R. and M.D.; methodology, A.R., M.D. and S.J.; software, S.J.; validation, S.J.; formal analysis, R.P.B.; investigation, A.R., M.D. and S.J.; resources, A.R. and M.D.; data curation, M.D. and R.P.B.; writing—original draft preparation, A.R. and M.D.; writing—review and editing, M.D. and R.P.B.; visualization, A.R. and S.J.; supervision, M.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: "Not applicable" for studies not involving humans or animals.

Informed Consent Statement: "Not applicable" for studies not involving humans.

Data Availability Statement: Data is contained within the article or supplementary material.

Acknowledgments: The authors would like to express their gratitude to JSC, "Peikko Lietuva" and JSC, "Peri Lietuva" for their technical support.

Conflicts of Interest: The authors declare no conflict of interest.

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