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Experimental verification of the energetic model of the dry mechanical reclamation process

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Abstract

The experimental results of the dry mechanical reclamation process, which constituted the bases for the verification of the energetic model of this process, developed by the author on the grounds of the Rittinger's deterministic hypothesis of the crushing process, are presented in the paper. Used foundry sands with bentonite, with water-glass from the floster technology and used sands with furan FL 105 resin were used in the reclamation tests. In the mechanical and mechanical-cryogenic reclamation a wide range of time variations and reclamation conditions influencing intensity of the reclamation process – covering all possible parameters used in industrial devices - were applied. The developed theoretical model constitutes a new tool allowing selecting optimal times for the reclamation treatment of the given spent foundry sand at the assumed process intensity realized in rotor reclaimers - with leaves or rods as grinding elements mounted horizontally on the rotor axis.

Keywords: Waste management, Used sand, Reclamation, Rittinger's theory

1. Theoretical model of bonds destruction in dry mechanical reclamation processes – on the bases of the Rittinger's theory

Complexity of reclamation processes, consisting of several procedures of used foundry sands treatment, starting from the preliminary preparations, via the secondary reclamation and up to the final working of the reclaimed material, is the reason that this topic has not been fully covered in accessible references. Energetic problems of the reclamation can be considered from the point of view of energetic hypotheses, while one of them is the deterministic hypothesis of material crushing acc. to Rittinger.

The oldest, chronologically, hypothesis concerning the material crushing process is the Rittinger's one [1, 8]. As the basic for his theory, Rittinger assumed the observed phenomenon of proportionality of the energy consumed in material crushing to the obtained in this process surface increases of the grain set. He stated, among others, that „crushing works are corresponding to degrees of fineness".

The specific work acc. to Rittinger equals:

$$L_R = L_0 \cdot \Delta F \quad , \tag{1}$$

where:
L_0 – work necessary for obtaining the unit surface increase; J/m^2 (J/cm^2),
ΔF – surface increase of material as the result of crushing; m^2 (cm^2).

The Rittinger's theory is used in practice for designing of crushing devices and for forecasting the effectiveness of treatment processes [2, 3].

Physical similarity of a matrix grains liberation from coatings of binding agents to the crushing process as well as widely used and standardized tests of grain composition allowing to estimate the specific surface changes of the reclaimed matrix on the basis of sieve analysis, substantiated the application of this hypothesis to the mechanical reclamation processes.

1.1. Determination of an increase of the theoretical specific surface of the material due to the reclamation

Considering, in compliance with assumptions concerning the ideal model, that quartz grains are spheres of a substitute diameter d_Z, and the thickness of a binding agent coating equals g, it is possible to determine the diameter of an individual quartz grain coated with a binding agent: $d_A = d_Z + 2g$.

The thickness of the used binding agent coating on the surface of quartz grains can be calculated from the dependency, which takes into account volumes of: quartz grains coated with a binding agent (V_A), „clean" quartz grains (V_Z) and used binding agent (Vg):

$$V_A = V_z + V_g \quad ; V_z = \frac{\pi \cdot d_Z^3}{6} = \frac{m_z}{\rho_z} ; \; V_g = U_m \cdot V_z \cdot \frac{\rho_z}{\rho_g} . \quad (2)$$

The thickness g of the used binding agent coating is determined by the equation:

$$g = \frac{d_Z}{2} \cdot \sqrt[3]{(1 + U_m \cdot \frac{\rho_z}{\rho_g}} - d_Z = \frac{d_Z}{2} \cdot \left(\sqrt[3]{(1 + U_m \cdot \frac{\rho_z}{\rho_g}} - 1 \right), \quad (3)$$

where: V_A – volume of quartz grains coated with used binding agent; m^3 (mm^3),
Vz – volume of quartz grains; m^3 (mm^3),
Vg – volume of used binding agent; m^3 (mm^3),
ρ_g - density of used binding agent; kg/m^3 (g/mm^3),
ρ_z - density of sand grains; kg/m^3 (g/mm^3),
d_Z – diameter of a quartz grain; m (mm),
U_m – mass fraction of a binding agent in relation to sand grains.

It was assumed in the model that from one particle of used binding agent of a diameter d_A, two kinds of material are obtained in the secondary reclamation process:

- reclaimed matrix, without coating of used binding agent,
- coating of used binding agent constituting a dust fraction in the reclaimed material.

The theoretical surface increase of used foundry sands together with the participation of dust fraction can be calculated on the basis of the following formulae:

- Number of grains of used foundry sand falling to the material unit volume [1/m^3] or (1/mm^3) equals:

$$n_A = \frac{1}{V_A} = \frac{6}{\pi \cdot (d_Z + 2 \cdot g)^3} , \quad (4)$$

- Number of grains of used foundry sand after the reclamation (but before the final classification) falling to the unit volume of material [1/m^3] or [1/mm^3], analogically equals:

$$n_Z = \frac{1}{V_Z} = \frac{6}{\pi \cdot d_Z^3} . \quad (5)$$

Theoretical surface of grains in the unit volume [m^2/m^3] or [mm^2/mm^3] equals respectively:

$$\Sigma F_A = n_A \cdot F_{ZA} = n_A \cdot \pi (d_Z + 2 \cdot g)^2 = \frac{6}{d_Z + g} , \quad (6)$$

$$\Sigma F_Z = n_Z \cdot F_Z = n_Z \cdot \pi \cdot d_z^2 = \frac{6}{d_Z} . \quad (7)$$

Thus, the increase of the material specific surface falling to the unit volume due to the reclamation equals:

$$\Delta F_V = \Sigma F_Z - \Sigma F_A = \frac{12 \cdot g}{d_Z (d_Z + 2 \cdot g)} . \quad (8)$$

Surface change falling to the mass unit [m^2/kg] or [mm^2/g] equals:

$$\Delta F_m = \frac{12 \cdot g}{\rho_z \cdot d_z (d_z + 2 \cdot g) \cdot (1 + U_m)} . \quad (9)$$

1.2. Procedure of estimating changes of the matrix theoretical specific surface of the reclaimed used foundry sand

Changes of the theoretical specific surface are estimated in the following way:

- a substitute diameter value d_A is estimated on the basis of the sieve analysis of spent foundry sand, prepared in a typical way (preliminary reclamation) and intended for the secondary reclamation,
- on the basis of the sieve analysis executed after the reclamation however, before the final classification, the substitute diameter d_Z is estimated followed by estimation of the coating thickness g – on the grounds of the formulae:

$$d_A = d_Z + 2 \cdot g ; \qquad g = \frac{d_A - d_Z}{2} . \quad (10)$$

An increase of the theoretical specific surface [m^2/kg] or [cm^2/g] is expressed by the difference of this value after the reclamation however, before the final classification (F_Z) and the theoretical specific surface of spent foundry sands before the reclamation (F_A), which results from equation (6). The specific surface is obtained as the result of the sieve analysis where it has a symbol S_t:

$$\Delta Fm = F_Z - F_A . \quad (11)$$

Knowledge of the increase of the matrix theoretical specific surface and its initial mass (mm) allows to calculate the total work of crushing:

$$\sum L_R = m_m \cdot L_0 \cdot \Delta F_m , \qquad [J]. \qquad (12)$$

For the description of phenomena in the mechanics of braking up of various brittle materials the Rittinger's material numbers, R, are used. They determine – in approximation – the material surface value formed due to the expenditure of energy unit [8].

$$R = \frac{1}{L_0} \quad , [cm^2/J] \quad . \qquad (13)$$

Rittinger's number reciprocity is the work L_0 - necessary for obtaining the unit of surface increase – according to equation (12).

1.3. Procedure of determining Rittinger's material numbers, R

The presented energetic model of the reclamation process developed on the grounds of the Rittinger's theory requires experimentally determined material numbers. Grain composition functions were applied for their determination in the model.

Procedures aimed at the determination of this number are schematically presented in Fig. 1, from which one can notice the comparative character of the method with the reference material being a fresh high-silica sand.

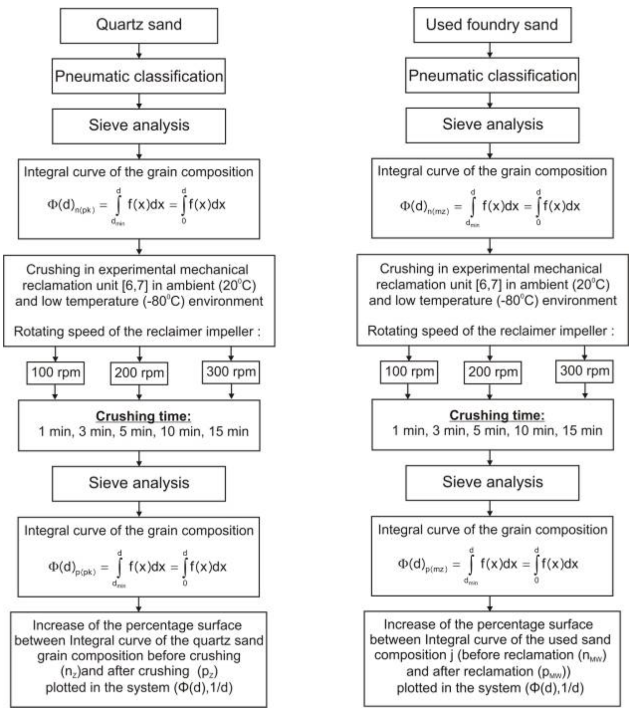

Fig. 1. Schematic presentation of the method of determination the Rittinger's material number R;Z – fresh quartz sand, MW – used foundry sand [6, 8]

The work related to removal of used coatings from the matrix grains (L_{RMW}) is identified with the work of crushing according to the Rittinger's theory (L_R), which is expressed by:

$$L_R = L_{R\,MW} \qquad (14)$$

The determination of the effectiveness of the reclamation treatment in a mechanical device is based on the comparison - in the given, similar reclamation conditions - of the increase of the specific surface of two materials:

– High-silica sand constituting sand grains – as the reference material of the known value of the Rittinger's number (17.56 [cm^2 /J),
– Used foundry sand with the binding agent under investigation - of the unknown value of the Rittinger's number.

Technologically justified process of the liberation of sand grains from coatings of used binding agents should not be carried longer than for the time, in which the coating thickness becomes zero (g = 0). Work proportionality for both materials is – in this case - maintained, which is expressed by:

$$L_{0MW} = \alpha \cdot L_{0Z} \qquad (15)$$

where:
L_{0MW} – expenditure of work for a unit increase of the theoretical specific surface of used binding agent; J/m^2 (J/cm^2),
L_{0Z} – expenditure of work for a unit increase of the theoretical specific surface of high-silica matrix; J/m^2 (J/cm^2),
α - coefficient determined on the basis of the ratio of areas contained between integral curves of the grain composition of feed and product plotted in the coordinate system (1/d, Φ(d)) for pure high-silica sand and for used foundry sand with the given binding agent.

The plot of grain composition in the coordinate system (1/d, Φ(d)) is performed on the basis of the sieve analysis, after each reclamation cycle [8]. Then the percentage surface increase, between curves of the grain composition of initial sand and used foundry sand undergoing the reclamation, is calculated.

The calculated Rittinger's number for the binding agent of coating is given by the equation:

$$R_{MW} = \frac{\Delta F_{MW}}{\Delta F_Z} \cdot R_{SiO_2} \qquad (16)$$

1.4. Determined values of Rittinger's material numbers of the investigated used materials

Rittinger's material numbers, R, were determined experimentally according to the described method. Experiments were performed in the experimental mechanical and mechanical-cryogenic reclaimers described in the papers [6, 8]. Tests were performed for the following spent foundry sands:

1) Used sand with bentonite GEKO S - B,
2) Used sand with water-glass (floster technology) -S,
3) Used sand with synthetic FL 105 resin and GS 03 hardener – Z.

The obtained calculation results performed according to the described procedure are listed in Table 1.

Table 1.
Experimentally determined Rittinger's material number, R, for used binding agents from the investigated technologies

Type of material	Reclamation temperature	α	Rittinger's material number R
	[K]	[/]	[cm^2/J]
Fresh quartz sand	ambient (288 -293)	-	17,56
Fresh quartz sand	low (192-205)	1,41	24,76
Used bentonite sand	ambient (288 -293)	3,17	55,67
Used bentonite sand	low (192-205)	3,06	75,86
Used water glass sand	ambient (288 -293)	1,28	22,48
Used water glass sand	low (192-205)	1,78	44,08
Used furan sand	ambient (288 -293)	1,21	21,24
Used furan sand	low (192-205)	1,27	31,69

2.Verification of the developed theoretical model

The knowledge of an increase of the theoretical specific surface of the material $\Delta Fm = S_t$ (known from the sieve analysis) after the reclamation as well as the Rittinger's material number, R, needed for causing this change, are the necessary conditions for the estimation of the reclamation work – according to equation (12):

$$L_R = m_m \cdot L_0 \cdot \Delta F_m = m_m \cdot \Delta F_m \cdot \frac{1}{R} \quad ; J \qquad (17)$$

Work values of the preliminary, secondary and total reclamation, when taking into account that the grain of the reclaimed material corresponds to a characteristic diameter d_A , are presented in Table 2.

Table 2.
Work of the preliminary, secondary and total reclamation calculated on the basis of the modified Rittinger's model for the reclaimed material grain of a characteristic diameter d_A

Kind of used foundry sand – reclamation method	Reclamation work L_R		
	Primary L_{RP}	Secondary L_{RW}	Total L_R
	[J/kg]	[J/kg]	[J/kg]
Used bentonite sand (B) – MECHANICAL RECLAMATION (RM)	70,66	71,46	142,12
Used bentonite sand (B) – MECHANICAL-CRYOGENIC RECLAMATION (RK)	49,28	52,65	101,93
Used water glass sand (S)– MECHANICAL RECLAMATION (RM)	61,52	52,13	113,65
Used water glass sand (S)– MECHANICAL-CRYOGENIC RECLAMATION (RK)	31,37	26,59	57,96
Used furan FL 105 Sand (Z) – MECHANICAL RECLAMATION (RM)	65,85	30,79	96,64
Used furan FL 105 Sand (Z) – MECHANICAL-CRYOGENIC RECLAMATION (RK)	44,25	20,69	64,94

Table 3.
Secondary reclamation work calculated on the basis of the modified Rittinger's model recounted to 1% of the removed used binding agent

Kind of used foundry sand – reclamation method	Secondary reclamation work recounted to the amount of a binding agent L_{RW}/1%
	[J/(kg x 1%)]
Used bentonite sand (B) – MECHANICAL RECLAMATION (RM)	8,97
Used bentonite sand (B) – MECHANICAL-CRYOGENIC RECLAMATION (RK)	6,58
Used water glass sand (S)– MECHANICAL RECLAMATION (RM)	14,90
Used water glass sand (S)– MECHANICAL-CRYOGENIC RECLAMATION (RK)	7,58
Used furan FL 105 Sand (Z) – MECHANICAL RECLAMATION (RM)	18,11
Used furan FL 105 Sand (Z) – MECHANICAL-CRYOGENIC RECLAMATION (RK)	12,17

The preliminary reclamation requires similar or even higher work expenditure than the secondary reclamation. Thus, the preparation of sands and properly performed preliminary reclamation significantly determines the total reclamation effect. Analysis of the obtained data indicates that the highest secondary reclamation work is needed for used sand with bentonite (B), then for used sands from floster technology (S) and then for used sands with FL 105 resin (Ż). An application of the mechanical-cryogenic process decreases work expenditure for the removal of used binder coatings from matrix grain surface, in all analysed cases. This is partially related to changes of the Rittinger's material number in a lowered temperature, but mainly to an increased brittleness of a binding agent.

While the highest value of the calculated work is in the case of reclamation of used sands with bentonite, it does not mean that this sand has the worse reclaimability. Such result seems to be due to the highest percentage fraction of binding agent in this sand composition. Thus, taking into account the amount of binding agent being removed from matrix grain surfaces forms a new possibility of arrangement of used foundry sand and means of their reclamation treatment in dependence of energy-consuming. The calculation results of the secondary reclamation work expended for removal of 1% of used binding agent – listed in Table 3 – confirm this conclusion. Thus, this information supplementing currently known tests of assessing reclaimability, is important from the economic point of view of the reclamation treatment.

3. Verification of reclamation effects of matrix from used foundry sands with bentonite

Reclamation work values calculated on the basis of changes in the specific surface of used foundry sands with bentonite undergoing the mechanical treatment in the whole range of rotational speeds, are presented in Fig. 2. As can be seen, the work value shown in Table 2 was not reached. The mechanical-cryogenic treatment of the same sands does not satisfy the condition only at n = 100 rot/min.

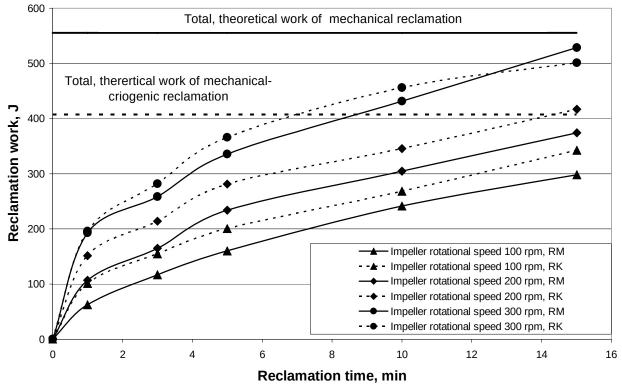

Fig. 2. Reclamation work of the matrix from used foundry sands with bentonite and the determined levels of the total, theoretical reclamation work for the applied reclamation methods (data for 4 kg of used sands)

The results of comparison of the reclamation work in relation to reclamation effects expressed by a binding agent content in the reclaimed material after the reclamation time equal 15 min - are given in Table 4.

Table 4.
Comparison of the reclamation work of used foundry sands with bentonite with the decrease of the binding agent content in the reclaimed material (reclamation time = 15 min)

Reclamation method – rotor rotational speed of the reclaimer *)	Decrease of the binding agent content in the reclaimed material	Actual reclamation work in relation to the theoretically calculated total reclamation work
	%	%
RM 100	37,33	53,64
RM 200	50,25	67,30
RM 300	65,23	95,16
RK 100	59,33	84,04
RK 200	69,25	102,27
RK 300	77,61	123,01

*) RM – mechanical reclamation, RK – mechanical-cryogenic reclamation, 100, 200, 300 – rotational speed of the system of impact-grinder of the reclaimer, rot/min

The obtained results indicate that in parallel to the percentage increases of the reclamation work, calculated on the basis of the actual data from the sieve analysis, the purification degree of matrix – measured by diminishing content of binding agent in the reclaimed material - increases. The observed discrepancy between the work value and binding agent content can be explained by significant difference between the actual and ideal conditions, mainly: non-spherical grain shapes (shape factor W_K = 1.20), occurrence of irregularities of surface, hollows and slits, where binding agents can be deposited. In the case of cryogenic reclamation – after 15 minutes and the final pneumatic classification – crushing of matrix grains occurs at rotational speeds 200 and 300 rot/min, of the reclaimer.

4. Verification of reclamation effects of matrix from used foundry sands with water-glass from floster technology

The results of the reclamation of used sand, with water-glass, indicate that work values presented in Table 2 was reached during the mechanical-cryogenic treatment, while the mechanical reclamation meets the condition for n = 200 and 300 rot/min only.

Analysis of the dependence of the purification degree of matrix grains from the actual reclamation work, calculated on the basis of the reclaimed material sieve analysis, is presented in Table 5. It has been assumed in this case, that the Na_2O content in the reclaimed material is the most reliable information for the estimation of the matrix grains purification degree. Analysis of data from Table 5 indicates that in the case of used foundry sand with water-glass increase of the calculated reclamation work corresponds to a decreasing Na_2O content in the reclaimed material. The matrix of this moulding sand constituted a fresh high-silica sand of a shape factor equal 1.18. The shape factor W_K - increased to 1.38 - for the reclaimed materials after the final classification, indicates that the mechanical-cryogenic reclamation performed at the rotational speed of reclaimer equal 300 rot/min, after 15 minutes causes crushing of matrix particles.

Table 5.
Comparison of the calculated reclamation work of the used foundry sands with water-glass (floster technology) with the obtained diminishing of Na_2O content in the reclaimed material (reclamation time = 15 min)

Reclamation method – rotor rotational speed of the reclaimer *)	Decrease of the Na_2O content in the reclaimed material	Actual reclamation work in relation to the theoretically calculated total reclamation work
	%	%
RM 100	64,39	76,06
RM 200	69,56	98,19
RM 300	72,09	127,23
RK 300	75,32	204,94

*) RM – mechanical reclamation, RK – mechanical-cryogenic reclamation, 100, 200, 300 – rotational speed of the system of impact-grinder of the reclaimer, rot/min

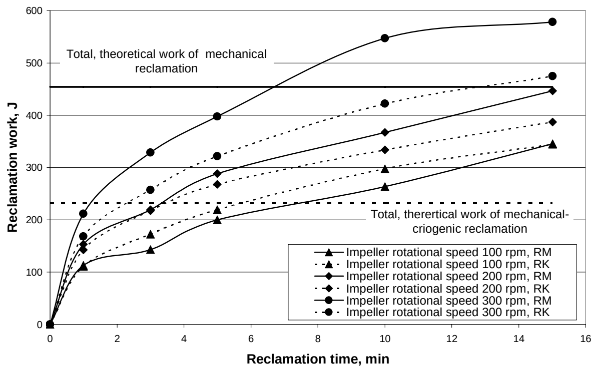

Fig. 3. Reclamation work of matrix from used foundry sands with water-glass and the determined levels of the total, theoretical reclamation work for the applied reclamation methods (data for 4 kg of used sands)

5. Verification of the reclamation effects of matrix from used foundry sands with FL 105 resin

Graphs of the reclamation work versus time during the reclamation process of the used foundry sand with FL 105 resin are presented in Fig. 4. The condition of obtaining the reclamation work level at least equal to the total theoretically calculated reclamation work is met in the applied time span. All options of the mechanical-cryogenic reclamations and two speeds of the mechanical reclamation (n = 200 and 300 rot/min.) fulfill this condition. Table 6 illustrates the percentage lowering the ignition loss of the reclaimed material together with the corresponding reclamation work versus the theoretically calculated total reclamation work. The analysis of results confirms previous observations, that used foundry sands with resin are the most difficult to reclaim by means of the mechanical and mechanical-cryogenic treatment.

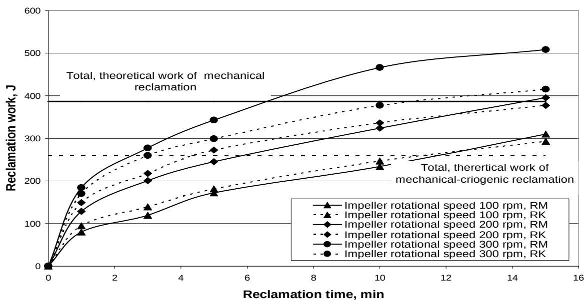

Fig. 4. Reclamation work of the matrix from used foundry sands with FL 105 resin and the determined levels of the total, theoretical reclamation work for the applied reclamation methods (data for 4 kg of used sands)

Table 6.
Comparison of the calculated reclamation work results of used foundry sands containing FL 105 resin with the lowering the ignition loss of the reclaimed material (reclamation time = 15 min)

Reclamation method – rotor rotational speed of the reclaimer *)	Decrease of the LOI in the reclaimed material	Actual reclamation work in relation to the theoretically calculated total reclamation work
	%	%
RM 100	37,00	80,20
RM 200	42,88	102,29
RM 300	48,63	131,43
RK 100	43,50	112,81
RK 200	49,25	145,15
RK 300	53,75	159,78

*) RM – mechanical reclamation, RK – mechanical-cryogenic reclamation,
100, 200, 300 – rotational speed of the system of impact-grinder of the reclaimer, rot/min

6. Conclusion

The performed tests and investigations allow to present the following conclusions:

1. The presented experimental investigations indicate that the theoretical model of the reclamation process developed on the basis of the Rittinger's theory [1], with its further modifications [2, 3, 8], corresponds to the reality in a satisfying manner, which can be considered its verification.
2. Model of liberation of matrix grains from spent binding agents - developed on the grounds of the modified Rittinger's hypothesis [2, 3, 8] – is based on experimentally determined material numbers R for typical binding agents being applied in moulding sands. This allows to propose a more unified assessment system of reclamation effects as well as energy consumption related to these processes.
3. The possibility of utilising the routine sieve analysis of the reclaimed material to determining Rittinger's material numbers, R, on which bases an approximate compliance of spent foundry sands for the mechanical reclamation can be estimated, was pointed out.
4. However, the proposed system of forecasting mechanical reclamation effects as well as determining energy-consumption of treatment should be periodically confronted with traditional, technological methods of determining the reclaimability, since this will verify fulfilling, by the reclaimed material, special requirements e.g. concerning the limiting content of contaminations.

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