Using a Loesche VRM, trials were carried out in order to determine the extent to which the constituents of concrete waste could be made suitable by a special recycling process for use as a substitute for the natural rock fraction in components. In this process, the employment of suitable separation equipment played a crucial role.

1 Summary
This article describes a new process for the separate recovery of the components of concrete waste by means of selective comminution in combination with dry separation by density. The process is based on a Loesche roller mill, which liberates the gravel and sand fractions in a non-destructive manner. Post-separation of the coarse fraction using an air jiggling machine or dry fluidized bed separation ultimately produces a recyclate of such a good quality that it can be used to completely replace the natural rock fraction. Pilot results of the selective comminution are presented and it is demonstrated that under equal concrete manufacturing conditions the obtained recyclates (recycled gravel, sand and filler) are all just as good as, if not superior to, the natural rock fraction.

Moreover, utilisation of filler consisting mainly of ground hardened cement paste fraction promises residual reactivity. In conclusion, the schematic diagram of the process is presented. This process also enables the alternate grinding of different raw materials, such as granulated blast furnace slag, clinker and concrete in a single plant.

2 Introduction, state of technology
Currently, sustainability, careful use of resources and critical consideration of the specific CO₂ emis-
sion of the production chain are catchphrases often used in connection with the supply of raw materials. At the same time, the extractive industries are making great efforts in many areas to establish high-quality raw material recycling processes. Naturally, this is also the case in the largest raw materials market, i.e. building materials.

In Germany, approx. 500 million tonnes of sand, gravel and natural rock are extracted annually. Approx. 35-40% of this is used for concrete production purposes [1-3]. Compared to this quantity of 180 million t of sand, gravel and natural rock, the annual amount of reclaimed building rubble is approx. 50-60 million t. This consists of slags, aerated concrete, glass, bricks and diverse extraneous materials, but also of up to 55-60% granulated concrete, natural rock and sand [8].

If the annual quantities of aggregates used in the production of concrete are compared to the theoretically recoverable quantities of concrete waste, the 180 million t of concrete aggregate compare to a theoretical quantity of 25-30 million tpa of recycled concrete: it is therefore theoretically possible to replace a maximum of 15% of the primary aggregates with recyclates. Although the recovery of building rubble and its natural rock and sand components for use in the concrete production process is often restricted by practical limitations due to impurity of the prepared products [9], efforts to produce high-quality recyclates are increasing both nationally and internationally.

A study into the use of granulated concrete recovered from building rubble carried out in 2010 by IFEU GmbH [5] was based on a concrete project for the use of granulated concrete instead of primary sands and gravels for new concretes. Furthermore, it is shown that it is becoming more and more complicated to obtain permits for new extraction areas and that particularly the consumption of near-natural land has become a sensitive issue in licensing procedures.

Expanding cities and city states such as Singapore, Rio de Janeiro and Sao Paulo suffer from limited availability of sand and gravel, from lack of space for depositing building demolition rubble and sometimes also from traffic conditions that prevent the transportation of building demolition rubble to sites outside the city. Ulsen [4] takes the example of circumstances in Brazil to present the possibility of preparing the concrete waste to produce a quality sand aggregate that is otherwise no longer available in the area of large cities, and to explore solutions for generating new concrete aggregates on the demolition site.

The current situation of building rubble processing in Germany is that conventional screening and crushing plants are used for producing aggregates for road construction (approx. 56%), path construction and earthworks (30%) and for other purposes (13%), but that up to now only 1% has been utilised for the concrete manufacturing process [10].

If crushed concrete granulate is used in the manufacturing of new concretes, the rate of addition is normally limited to 10% of the amount of primary aggregate. Higher addition rates are not employed as they often lead to an increase in water demand and consequently to a higher consumption of binding agent/filler and poorer workability. This problem can be remedied by selective comminution, provided that it is possible to reduce the concrete into its constituent gravel, sand and filler/hardened cement paste, as this would permit a larger amount of recycled building materials to be used in the concrete mixture.

A number of approaches to selective comminution exist. Impact crushing is often more selective than pressure crushing [4, 8]. High voltage fragmentation under water [12] and modifications of the jaw crusher process [11] have been successfully applied for selective comminution of concrete, but are still in the development phase.

The approach followed by Loesche, which was presented for the first time in April 2014 [14], also
has the objective of selectively reducing waste concrete to its individual components and thus to produce recycled raw materials whose quality is equal to that of primary raw materials. The precondition for this development was the employment of process technology and mechanical equipment that is available on the market, whose operating reliability has been comprehensively proven by decades of usage, and which can be planned and applied without difficulty for > 90% of the throughput rates of between 50 and 500 t/h that are usual in the aggregates sector.

3 Functions of a Loesche mill for selective comminution

The fundamental idea is to use a “Loesche mill”, a grinding unit that is normally employed for fine comminution, for reducing a material consisting of several components into its individual components, without involving an excessive amount of comminution work. The multicomponent material in this case is concrete, which essentially consists of three solid components:

- gravel
- sand
- hardened cement paste, the mixture of hydration products of water and cement

From the numerous measurement criteria that can be applied for characterising the strength of solid components, the authors decided to use the Vickers hardnesses of the individual components for the purpose of describing the comminution resistance. To enable this, a series of raw material tests was conducted at the Institut für Aufbereitungsmaschinen (Institute for Mineral Processing Machines) at the TU Bergakademie Freiberg, and the Vickers hardnesses were determined from polished sections prepared from relevant samples. Fig. 1 shows the great difference between the strength values of the examined individual concrete components.

Given such differences in strength as those determined in this case, it is appropriate to operate the comminution process in a manner that exclusively disintegrates the hardened cement paste/cement paste matrix and preferably leaves the other components in their original particle size. However, owing to the low strength of the hardened cement paste matrix, a gentle attritional pressure crushing is more appropriate for this purpose than a high-pressure crushing process.

Carried over to the principle of dry comminution of concrete rubble in a Loesche-type roller mill, the selected disintegration process is as schematically represented in Fig. 2. The feed material (1) is dumped onto the centre of the grinding table (2) and then carried under the grinding roller (3) by centrifugal force. A bed of material is formed between the grinding roller and the grinding table, the height of which is regulated by the dam ring around the outer edge of the grinding track. The material in the bed is subjected to a shearing, frictional compressive stress due to appropriate setting of the process parameters:

- grinding table rotation speed
- angle of the grinding rollers
- pressure of the grinding roller on the material bed
The roller mill required for this mode of material preparation has the same general design as the Loesche mills employed in the cement industry. The only difference – resulting from the need for a low contact pressure per unit area – is the design of the hydraulic pressure system of the grinding rollers. The mill works with simultaneous airflow and overflow operation. This means that a substantial flow of material is discharged through the louvre ring (4), even against the air stream. This is the first stage of material separation/classification, as lumpy and heavy material falls into the discharge system (8) due to gravity, despite the flow strength of the rising stream of air.

The air stream (5) entrains the finer and lighter material and transports it upward to the second classification stage, the dynamic classifier (6). This classifier collects the adequately fine-ground filler from the coarser material, the fine sand and the remaining mortar/hardened cement paste aggregates. These rejects pass through the classifier grit discharge cone (7) and are returned to the grinding process.

Depending on the size of Loesche mill, the feed material size can be as large as 100 mm. These particle sizes correspond to the normal product size range of a primary crushing plant for concrete rubble. As the iron reinforcing bars have already been removed from the material, it is ready for use in the disintegration process.

The objective of the comprehensive pilot plant tests was to demonstrate that the Loesche mill is able to perform this multi-stage process for transforming concrete granulate into a concrete aggregate, namely:

* Selective disintegration of the larger-sized feed fraction and cleaning of the surfaces
* Removal of the coarse fraction at the louvre ring
* Removal of the filler fraction at the dynamic classifier as a final product

In addition to achieving an effective selective disintegration and efficient classification, it is also necessary to separate the coarse and medium fractions in order to obtain a complete separation into the three products: gravel, sand and hardened cement paste. For this reason, dry density separation processes were used for these fractions (sand and gravel) in order to obtain pure natural sand and natural stone fractions as finished products of the process.

### 4 Tests at Loesche’s test plant

#### 4.1 Execution

All the tests for processing concrete rubble were conducted in a Loesche pilot plant using a test roller mill that is normally used for trials with feed materials in order to obtain the fundamental data for designing machines, processes and plants for the cement industry. The mill used is the LM 3.6/2 depicted in Fig. 3, which has a capacity of between 0.3 and 1.5 t/h, depending on the feed material and required product size.

A preliminary series of tests with a concrete rubble of undefined composition and a particle size distribution ranging from 4-16 mm immediately delivered a disintegration result that was optically so impressive (Fig. 4) that a comprehensive test plan was developed. Among the feed materials used for these tests were two types of concrete with defined compositions. Planning of the test programme, and evaluation of the measured data took place with the aid of proven DoE software (Design of Experiment). After conclusion of the grinding tests and evaluation of the product samples, the results were used as...
4 Products of the pilot test series. Left: ground filler, right: liberated concrete aggregate

Independently of whether concrete type 1 or 2 was fed to the mill, the achieved yield rate of filler product exceeded 85%. Moreover, the produced filler consisted of over 90% of ground hardened cement paste.

In parallel to that, the coarse grain fraction of >2 mm discharged from the mill contains a particle size mixture consisting to 60–70% of gravel with almost totally clean surfaces, that has obviously retained its natural round form. By contrast, the product with a density of below 2.5 t/m³ is a mixture of agglomerates consisting of coalesced and of unground mortar/hardened cement paste particles (Fig. 6). In this case, the yield of gravel is approx. 90%.

If the focus is placed on obtaining a well-cleaned gravel product with minimal adhesions and a minimal amount of coalesced components, the grinding circuit can be set such that the coarse grained product has a purity of 93–95%. In this case, the yield of hardened cement paste in the filler product rises to over 90%.

5 Setting parameters of the pilot plant LM 3.6/2 and effects on the products of the selective comminution process

Various concrete mixtures were produced in accordance with a standard formulation as feed materials for the tests. More detailed testing was performed with two types of concrete, the first with a quality of C 20/25 (30 MPa) – subsequently called concrete 1 – and the second with a quality of C 55 (60 MPa) – subsequently called concrete 2. To ensure greater operating reliability and to prevent blockages in the test-grinding plant, gravel with a maximum size of 8 mm was used for the concrete granulate production.

The compositions of the concretes specially produced for the tests are shown in Table 1. The stated compressive strengths relate to a hardening period of 28 days.

Tab. 1 Composition of the tested concrete qualities and of the respective hardened cement pastes

<table>
<thead>
<tr>
<th>Concrete formulation</th>
<th>Material strength (MPa)</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30000</td>
<td>60000</td>
<td></td>
</tr>
<tr>
<td>Concrete (total)</td>
<td>w.- %</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Gravel</td>
<td>w.- %</td>
<td>43.9</td>
<td>40.6</td>
</tr>
<tr>
<td>Sand</td>
<td>w.- %</td>
<td>26.5</td>
<td>25.7</td>
</tr>
<tr>
<td>Concrete granulate</td>
<td>w.- %</td>
<td>5.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Hardened cement paste</td>
<td>w.- %</td>
<td>24.6</td>
<td>28.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concrete formulation</th>
<th>True density (kg/dm³)</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.13</td>
<td>2.23</td>
<td></td>
</tr>
<tr>
<td>Hardened cement paste (total)</td>
<td>w.- %</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Cement</td>
<td>w.- %</td>
<td>19.2</td>
<td>35.9</td>
</tr>
<tr>
<td>Slag</td>
<td>w.- %</td>
<td>44.8</td>
<td>35.9</td>
</tr>
<tr>
<td>Limestone meal</td>
<td>w.- %</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Water</td>
<td>w.- %</td>
<td>35.8</td>
<td>27.7</td>
</tr>
<tr>
<td>Concrete chemistry</td>
<td>w.- %</td>
<td>0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Influenced factors and effects:

- Grinding force
- Feed mass flow
- Grinding table speed
- Dam ring height
- Classifier speed
- Volume flow
- Grinding bed height
- Mechanical separation/cleaning of components due to abrasion
- Purity of sand & gravel
- Fineness of filler

For evaluation of the tests, the density of the concrete aggregate was defined as approx. 2.5 t/m³, while the densities shown in Table 1 (2.13 and 2.23 t/m³) were taken as a basis for the filler.

The evaluation was performed exclusively for the produced gravel (2–8 mm) and the filler derived from hardened cement paste. In addition to the mass balancing of the test results into the products sand, gravel and filler, the coarse products discharged from the mill were also subjected to a float/sink analysis at a density of 2.5 t/m³.

On the basis of the mass balances of the tests and the analyses of the products, the following separation results were calculated and the following findings were derived:

- Independently of whether concrete type 1 or 2 was fed to the mill, the achieved yield rate of filler product exceeded 85%. Moreover, the produced filler consisted of over 90% of ground hardened cement paste.
- Parallel to that, the coarse grain fraction of >2 mm discharged from the mill contains a particle size mixture consisting to 60–70% of gravel with almost totally clean surfaces, that has obviously retained its natural round form. By contrast, the product with a density of below 2.5 t/m³ is a mixture of agglomerates consisting of coalesced and of unground mortar/hardened cement paste particles (Fig. 6). In this case, the yield of gravel is approx. 90%.
- If the focus is placed on obtaining a well-cleaned gravel product with minimal adhesions and a minimal amount of coalesced components, the grinding circuit can be set such that the coarse grained product has a purity of 93–95%. In this case, the yield of hardened cement paste in the filler product rises to over 90%.
although the filler product produced then has a hardened cement paste purity of only 60-70%.

* The grinding circuit operates with absolute reproducibility, independently of the feed material (concrete 1 or 2). This ensures accurate setting with regard to the required characteristics of the individual products.

* Subsequent cleaning of the coarse grained product (sand and gravel) by means of highly-selective density separation enables qualitative improvement of the fine and coarse aggregates. Dry separation systems, such as those successfully employed for coal and slag separation, are suitable for this post-cleaning stage. [15, 16]

4.2 Usability results
The usage of concrete granulate in new concrete is generally restricted to an amount of approx. 10%. Higher amounts increase the water demand, lower the strength and raise the necessary amount of binding agent additive. A typical concrete granulate from a conventional concrete rubble processing plant is compared in Fig. 7 to the material obtained as heavy product + 2 mm from the Loesche process. Just the optical impression of the two products is enough to show that the concrete recyclate produced by the Loesche process has greater resemblance to a sample of conventional natural gravel than to a typical recycled concrete rubble product.

The filler and 2/8 mm gravel products obtained from the pilot tests with the Loesche mill were tested for their usability in new concrete.

4.2.1 Usability of the gravel fraction
Concrete test blocks were produced using different mixtures of aggregates, but keeping a constant water-to-cement ratio and constant amount of added binder. Table 2 compares three comparable formulations and their results, which have been selected from the numerous test series. These formulations are mixtures of the following aggregate products:

![Particles from the coarse ground product, embedded in resin for microscopic examination. Left: light material (-2.5 t/m³), right: heavy material (+ 2.5 t/m³)](image-url)

![Concrete granulates. Upper: 2/8 mm after the Loesche process, lower: 4/30 mm, conventional](image-url)
Increase in compressive strength (MPa) after 28 days due to the usage of reclaimed filler compared to the inert additive of 30 weight-% of quartz sand.

- Natural 2/8 mm gravel and natural 0/2 mm sand: Designation: NA
- Recycled aggregates from a standard process, grain-size curve adapted to NA: RC
- Recycled aggregate from the Loesche process, grain-size curve adapted to NA: RCLM

Comparison of the results shows up the differences in the three formulations.

The concrete produced from natural gravel and RC material shows a reduction in material processing, indicated by the slump data, as well as lower compressive strengths than the concrete produced exclusively from natural material (strength reduction between 10 and 15 %). The characteristics of the formulation using natural aggregate (NA) and recyclate from the Loesche process (RCLM) was astonishing, because the produced concrete had comparable workability and also an increase in compressive strength of over 10 % (Tab. 2).

Possible explanations for the significantly higher compressive strength of concrete containing recycled aggregate from the Loesche mill are that due to the attritional stressing of the gravel particles their surfaces were roughened, resulting in improved bonding capability of the Calcium silicate hydrate (CSH) phases compared to the smooth surface of primary gravel particles, or that the remaining coating of fine hardened cement paste on the gravel particles promotes an improved adhesion of the new hardened cement paste.

4.2.2 Usability of the hardened cement paste fraction of the filler

In parallel with the employment of coarse and fine aggregates in competition with conventional aggregates, orientation tests were carried out in order to indicate the usability of the recycled filler from the Loesche mill (RCLM). For the scenario of reduced addition of binding agent (OPC), these tests had the aim of indicating the degree to which a RCLM filler develops a reactivity that contributes to the strength of the concrete.

Employing the reference cement CEM I 42.5 R (Dyckerhoff/Deuna), the tests examined the influence of the strength development in standard prisms in accordance with DIN EN 196 (storage time: 2, 7 and 28 days) for two samples of filler (hardened cement paste from the recycling tests of concrete qualities 1 & 2). The individual mixtures were as follows:

- 30 weight-% of filler concrete 1 + 70 weight-% of reference cement
- 30 weight-% of filler concrete 2 + 70 weight-% of reference cement
- Reference cement as initial binding agent (CEM I 42.5 R) (28-day value: 48.7 MPa)
- 30 weight-% of quartz sand (0/2 mm fraction) + 70 weight-% of reference cement

The quartz sand was employed as inert material with the purpose of being able to compare the increase in strength due to the RCLM filler.

The results of the compressive strength test after 28 days are shown in Fig. 8.

The increase in compressive strength due to the 30 % addition of RCLM filler, i.e. a filler with a content of more than 70 % ground hardened cement paste, proves that this filler possesses a substantial binding agent reactivity.
In the case of the highest value (RCLM filler from concrete 1), it can be seen that the replacement of 30% Portland Cement by 30% RCLM filler can compensate for more than half the loss of strength. Further testwork is currently being carried out to determine the extent to which future RCLM fillers composed of hardened cement paste from waste concretes will also have such high reactivity, and to answer the question regarding the cause of the strength increase resulting from the use of recycled gravels.

5 Plant concepts for waste concrete recycling

Normally, waste concrete processing consists of crushing, screening, removal of the reinforcing bars by magnetic separation and removal of wood, plastic and lighter mineral fractions from the building rubble by means of a dip tank (wet process) or air separator if dry separation is preferred. At the end of the 1990s, it was proven that targeted and selective separation in jiggling machines makes it possible to remove extraneous material up to a density far in excess of 1.8 t/m³ [6, 7].

Employing this principle, the described plant concept for producing aggregate materials from waste concrete combines disintegration in a Loesche mill with efficient density separation. In this case, dry separation systems are employed, as this is sensible and sound practice for use in combination with a dry grinding process.

Even though it is known that alternative wet separation processes with high selectivity are available, the performed initial orientation tests allow justified expectation that the employed dry separation process will enable good aggregate material quality to be achieved.

Fig. 9 presents a schematic representation of the process sequence. After the grinding, the overflow product (“rejects”) of the mill is separated from the sand and gravel fraction by screening. Next, density separation on an air jiggling machine [15] separates the portion of finished gravel from the coalesced components that are not yet completely disintegrated.

Similarly to the processing of the gravel fraction, the sand fraction is subjected to density separation in a fluidised bed [16], which selectively separates the heavy material (sand fraction) from the mortar fractions and not yet completely disintegrated hardened cement paste conglomerates, i.e. the light material.

The Loesche mill employed for the selective comminution essentially corresponds to the standard design used for grinding granulated blast furnace slag and cement clinker. This enables such a grinding plant to be used not only for processing waste concrete, but also for the production of further materials for the cement industry. This alternate usage (“co-grinding”) can represent an attractive technical and economic alternative in many cases. Due to the flexible operational mode of the Loesche mill and to the mill’s ability to change over from one type of feed material to another within just a few minutes, it would be practicable to use one and the same mill for alternately grinding concrete rubble, granulated blast furnace slag and possibly also cement clinker.

<table>
<thead>
<tr>
<th>Natural aggregates</th>
<th>w-%</th>
<th>100</th>
<th>50</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycled aggregates</td>
<td>w-%</td>
<td>0</td>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>Recycled aggregates from Loesche mill</td>
<td>w-%</td>
<td>0</td>
<td>0</td>
<td>50</td>
</tr>
<tr>
<td>Cement CEM I 52.5 R</td>
<td>kg/m³</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Water/Cement</td>
<td>0.37</td>
<td>0.37</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Plasticiser/cement</td>
<td>%</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Slump test 10 min</td>
<td>mm</td>
<td>256</td>
<td>255</td>
<td>259</td>
</tr>
<tr>
<td>Slump test 60 min</td>
<td>mm</td>
<td>232</td>
<td>185</td>
<td>225</td>
</tr>
<tr>
<td>Compressive strength 28 days</td>
<td>MPa</td>
<td>63</td>
<td>55</td>
<td>74</td>
</tr>
<tr>
<td>Compressive strength 56 days</td>
<td>MPa</td>
<td>74</td>
<td>63</td>
<td>82</td>
</tr>
</tbody>
</table>

Tab. 2 Comparison of the concrete properties after alternative usage of aggregates. NA = natural aggregate, RC = standard concrete recylcate, RCLM = Loesche concrete recylcate
Such a plant consists of 4 process stages:

a. Processing of the waste concrete to produce feed material for the concrete aggregate grinding plant, comprising coarse grinding, removal of iron and production of an intermediate material of the 0/60 (80) mm fraction (Fig. 10, pos. 3)

b. The feed system for granulated blast furnace slag/cement (Fig. 10, pos. 1)

c. The mill with separator, hot gas producer and filter system, both for the ultrafine grinding (4000-5000 Blaine), and for the selective disintegration into the coarse and fine particle ranges (Fig. 10, pos. 2)

d. Treatment of the coarse mill discharge material by means of a dry density separation process (Fig. 10, pos. 4)

All the process variants and partial processes have been tried and proven on an industrial scale.

6 Prospects

The global requirement for aggregate materials for the production of concrete is second only to that for water. Even though there is no scarcity problem in the case of aggregates, the principle of sustainability demands that the largest possible quantities of waste concrete should be returned to the cycle of materials. This requires recycling, i.e. the production of new raw materials from the waste concrete. These must be usable in the concrete production process without causing any loss of quality. Against the background that there are real shortages of concrete aggregates from natural materials in many parts of the world, the approach of selective comminution in the Loesche mill represents a contribution towards the achievement of a considerably higher amount of recycling. Ongoing project work is taking place in order to optimise the selective comminution in combination with a suitable density separation system, as are detailed investigations of the application possibilities for the products.

REFERENCES