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Processing Disaster Debris Liberating Aggregates for Structural Concrete


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Abstract

Worldwide, the removal of debris and reconstruction is requested when natural disasters and conflicts cause damaged or collapsed buildings. The on-site recycling of concrete waste into new structural concrete decreases transport and production energy costs, reduces the utilization of raw materials, and saves the use of limited landfill space. The application of recycled concrete aggregates (RCA) in structural concrete is currently limited, since concrete recycling involves application as road base material or in non-structural concrete with low strength requirements. Applying an optimised crushing method could improve the applicability of RCA in structural concrete.

The quality of the initial concrete investigated is unknown, and embedded defects influence the quality of the final concrete made with RCA. Separating the hardened cement paste (HCP) from the aggregates through optimised crushing minimises the influence of the initial concrete on the quality of concrete made with RCA. In turn, the HCP can be extracted, reducing water absorption and minimising workability problems. Through this, optimised crushing makes the application of recycled concrete into new concrete far less troublesome, and therefore widely applicable and highly suitable for post disaster areas.

This study primarily looks into the influence of the optimised crushing process on the resulting particles of the produced RCA. For this, concrete demolition waste is passed through the optimised crusher three times. An initial visual assessment of the RCA produced is made and the specific aggregated density measured shows promising results regarding aggregate quality.

Keywords: Disaster Recovery, Construction and Demolition Waste, Recycled Concrete Aggregates, Optimised Crushing, Particle Size Distribution, Specific Density

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Introduction

Emergency response innovation
Within the framework of the EU project S(P)EEDKITS, this study into the production of aggregates for quality concrete from debris using optimised crushing has been performed. The main objective of the S(P)EEDKITS project is to develop so-called SPEEDKITS: rapid deployable kits for emergency response units. Guided by best practice guidelines from humanitarian organisations, these solutions will also be SEEDKITS, i.e. the kits form the seed for the long term self-recovery process in the post disaster period. The overall project enlists 5 themes on improvement of emergency response, namely system design (modularity, packaging, and tracking), shelters, facilities (water & sanitation), deployment and transport, and infrastructure (medical, communication, energy & re-building). By the end of the project in 2016, all developed solutions are to undergo extensive testing in a representative test case, preferably in an actual field-test.

A two-pronged kit for debris recuperation is being developed within this context: processing post-disaster debris into quality aggregates and the reuse of this material into new concrete applications. By combining these solutions, the reuse of the debris is optimised so that nothing is lost, and the demolished material becomes part of the new infrastructure.

Next to the demands regarding output quality, a post disaster application involves unique requirements as transportability (20 ft shipping container), affordability, simplicity, the use of as many human resources as possible in a safe manner and a low and easy level of maintenance preferably with local means and materials.

Modular, rapid deployable clearing kit
Debris clearance and crushing are not new to post-disaster areas. Neither is a mobile setup for mineral size reduction, fractioning and oversize refeeding. In Figure 1, an early model of such processing equipment is shown; here a rotary screen, jaw crusher and bucket conveyor can be distinguished.

![Figure 1: Early mobile aggregate production setup [1]](image)

However, the upcycling of the material into new structural concrete instead of low grade reuse or landfilling is innovative in this sector. After considering the full range of options (from manual labour to operating a full scale plant), the decision has been made on a capacity of 10-15 ton/hour. Compared to industrial standards, this capacity is rather low. However, this is supported because it enables ease of transport, rapid deployment, on-site mobility (even in an urban area), and limited investments. Additionally, both a manual and a (semi-)automated process can be supported with this scale of operation, thus employing local people and stimulating the rehabilitation of the local economy. This approach is supported by the
humanitarian actors represented within the S(p)eedkits consortium (International Federation of Red Cross and Red Crescent Societies, Médecins Sans Frontières). This in turn does not mean the impact should be small scale. Multiple kits can be deployed in parallel and processing and/or logistic equipment can be scaled up to enable a (semi-)automated approach (viable from a seeding perspective).

For demolition concrete or concrete debris to be applied into new concrete as recycled concrete aggregates (RCA), the maximum particle size needs to match that of a prescribed concrete mix design. Generally, a size reduction action is therefore needed. In order to be able to design a concrete mixture, based on the foreseen application and type of concrete, a specific number of different aggregates size ranges is desired. By screening or sieving, the material is separated into the desired size fractions and a potential oversize fraction can be returned for further size reduction.

The best case scenario would be when solely reclaimed materials and no virgin aggregates have to be used. Figure 2 shows the schematic concrete production process. When virgin aggregates are (partially or fully) substituted with RCA the process in the green area is applied. However, the original supply chain remains intact for when reclaimed aggregates are not produced in the right proportions or when complete substitution is not applicable.

Selection of crusher type
Numerous size reduction, so-called crushers, can be applied. Most crushing equipment originates from mining where a size reduction of homogeneous minerals is pursued. Even though concrete has a great resemblance to these materials, by nature it is heterogeneous. Because of this, the quality of the produced RCA greatly depends on the applied reduction method.

Jaw crushers provide the best particle size distribution (PSD) for recycling, cone crushers are only applicable for secondary crushing, swing hammer mills are rarely applied, and impact crushers are less sensitive to non-crushable contaminants, crushing cement and aggregates alike [2, 3]. Other possible crushing techniques are gyratory crushers (high capacity), roll crushers (which produce few fine materials), gravity stamps (no output control), and Bradford breakers (suitable for friable materials) [1, 4].

Several experimental techniques are recently developed specifically for the recycling of concrete; all these aim at separating aggregates from hardened cement paste. These
techniques comprise smart crushing (low energy consumption, low tech) [5–8],
electrodynamic fragmentation (large energy consumption, high tech) [9],
microwave fragmentation (large energy consumption, high tech) [10], and
heating and rubbing (high energy consumption, low tech) [9, 11].

**Optimised crushing**
The crushing technique investigated in this study is a jaw crusher-based crusher,
specifically designed for concrete recycling. The objective of this type of crushing
is to separate concrete into its constituents (sand, gravel and cement paste) based on
the principle of Smart Crushing shown in Figure 3 [5]. In contrast to this figure,
the applied optimized crusher makes use of a plate hinged from the stationary
crushing plate in order to contain material between the crushing plates.

![Figure 3: Principle drawing of Smart Crushing](image)

Currently applied crusher types are mainly used solely with the aim of reducing
particle sizes, crushing all component materials randomly; in the case of concrete,
this will include crushing through the aggregates as well as through the cement
paste. Since the intention is to separate concrete into its composing materials
without the risk of the components themselves being damaged, the crushing force
is adjusted to be intermediate between the compressive strength of the aggregates
and that of the hardened cement paste. Hereby, the paste yields under the applied
force while the aggregates stay intact.

The attached (residual) mortar is the main concern in using recycled concrete
aggregates in new concrete; it accounts for the main difference between natural
aggregates and RCAs. The attached paste on incorporated recycled concrete
aggregates is the main factor causing impaired quality of the new concrete.

Preceding studies investigated the properties (PSD, density, oxide and mineralogical
composition) of a number of recycled concrete fractions, obtained through both
conventional jaw crushing and optimized crushing. Results showed that, compared
to conventional jaw crushing, the generated RCA can have a significantly lower
amount of residual attached mortar when the optimized technique is applied [5–8].
Furthermore, application of such RCA, practically free of attached cement paste,
completely replacing river aggregates in mortars, has shown to be without loss of
mechanical properties. Especially for short curing times, the
mechanical properties of the RCS mortars proved to be promising, achieving higher strengths than the reference samples.

**Selection of sieve**

Since no crusher will produce the optimal PSD for the production of concrete directly, the particle composition should be tailorable and oversize aggregates need to be re-fed into the crusher. At minimum, sand, gravel, and oversize gravel fractions need to be separated in order to make a proper concrete mixture.

In general, the fines released when recycling concrete tend to negatively influence the quality of the new concrete [3, 12]. Because of this, extraction of the fine fraction from the overall sand fraction is beneficial for the applicability of the RCA.

The processed concrete can contain various levels of moisture; the present water can cause agglomeration of the fines, potentially clogging the sieves. Although rinsing the aggregates (wet sieving) improves the separation of fines, minimising airborne particles and preventing clogging, fresh water might be scarce and brackish or salty water is to be avoided due to chloride inclusion into the new concrete [13, 14]. Air separation as addition to a screening step (allowing for the dry removal of fines) is not applicable because of transportation limitations and a single mechanical extraction step is therefore required.

Rotary drum screens, regularly applied in aggregate processing, are not applicable since they are both large and split off particles from small to large, maximising the load on the delicate fines screen. The modified rotary sieve design eliminates both disadvantages and is therefore a feasible option [15–17]. The downside to this design is that it has never been applied into any production process and teething problems, like the pegging of aggregates, are thereby to be expected. High-precision screening machinery (e.g. rotary vibrating screens) split off the top fraction first, are compact, and are industrially applied in dry fines sieving (e.g. flour); these are however delicate and transportation is therefore not recommended. Vibrating screens or flat-deck sieves are less delicate and applicable without problems. In contrast to most industrial screening equipment, where sieve decks are placed level or at a slight angle, the screens of sizers (by Mogenson [18]) are placed at a relatively large angle. Additional decks spread the load over a multitude of sieve decks, thereby greatly increasing the capacity and minimising the size of the equipment. The increased angle of the deck has a downside: in order to create a separation representative to a horizontal sieve deck, an increased mesh size is needed, which in turn results in less accurate particle separation. In contrast with other separation methods, this type of equipment has a high resistance to the deposition of material, clogging, pegging, and blockages resulting in a reliable operation with a minimum of maintenance. Based on the required properties, separation using a sizer is most suitable.

**Materials**

The investigated material originates from structural concrete produced in 1967 at the campus of the Eindhoven University of Technology and is released during a demolition project. Prior to obtaining the material for analysis, the structural elements had undergone pulverisation by means of a hydraulic jaw pulveriser, removing the rebar, and went through a crushing step using an excavator-operated bucket jaw crusher.

The majority of all concrete used within this study was produced using river aggregates; the global mix design of the concrete is however unknown.

**Methodology**

In this study, the minimum distance between the containment plate and the moving jaw (hereinafter called aperture) has been set at 30 mm.

Both initial material and the material produced through crushing have been sampled according to DIN EN 932-1 [19] from ‘1 m³ flexible intermediate bulk containers, and respectively from a conveyor. However, since the crushing tests are performed as a batch process, in contrast to a typical continuous process, the filling and emptying of the cavity
influences the properties of the produced materials. Therefore, samples are only taken after an initial “flush” with material and before emptying the crushers’ cavity. Prior to any further analysis, the material was pre-dried to an air-dry state [20] in an oven at 105 °C, eliminating the effect of agglomeration prior to sieve analysis. Subsequent of the sieve separation, the produced fractions were dried to an oven-dry state by drying the sample at 105 °C until constant mass was reached. All particle size analyses have been performed according to EN 933-1 and EN 933-2 [21, 22]. In addition to the mesh sizes described in EN 933-2 [22], additional sieve sizes (45 mm, 22.4 mm, 11.2 mm, 5.6 mm, 2.8 mm, 1.4 mm, 710 µm, 355 µm, 180 µm, 91 µm) were added, increasing the detail of the study. Simultaneously with the sieve analysis, the material is split in fractions for future analysis. Finally, the specific density of every fraction is determined using a He pycnometer (Micrometrics Accupyc 1340).

Results and discussion

Particle size distribution
According to prior studies, smart crushing is most effective after three passings through the crusher [6]. Figure 4 shows the PSDs for the initial material and the resulting PSD of three crusher passings at an aperture of 30 mm. The material produced at the 30 mm setting has a distinctively even shift in cumulative PSD. This is supported by the sieve fraction PSD which shows an inversion point, where more particles of a certain size are generated instead of being broken down around 22.4 mm. Next to that, a slight increase in fines and the fractions near 8.0 mm can be seen.

Overall, Figures 5 shows that where particles in the gravel size range tend to be influenced in a substantial manner by the crusher passages, the fractions within the sand and fines range are in general merely exposed to small changes in PSD.

Visual quality assessment
For the gravel fraction range, an initial visual indication of the effectiveness of separating the hardened cement paste from the aggregates and thereby the quality of the produced aggregates can be seen. Figure 5 depicts the 8 mm dry sieved (non-washed) gravel fractions produced. Based on the visual assessment of the produced material, rounded clean river aggregates (Figure 5a), aggregates with excessive cement paste attached (Figure 5b), and angular, broken aggregates are found (Figure 5c).

The angular shape is specifically found in the smaller size fractions. This is a non-natural shape for river aggregates, indicating aggregates have been broken either in the pre-crushing process or during the optimised crushing process.

Figure 6 shows the specific density of every fraction. Florea et al, [6] have related RCA density to aggregate content where 100% HCP compares to 2.30 g/cm$^3$ and 2.65 g/cm$^3$ equals 100% aggregate content. The measured densities relate well to this and a similar increasing trend up to 8 mm is seen.

Further analysis on the mineralogical composition of the fractions produced is needed to quantify the quality of the separating the aggregate from the HCP. The specific density however could indicate an increasingly lower HCP content up to 8 mm. Above 11.2 mm increasingly more HCP is witnessed, which corresponds to the reduced density.

**Conclusions**

The aggregate production method investigated is able to produce reclaimed gravel and sand fractions which are optically rather clean of cement paste out of concrete debris; this is supported by the specific density of the different fractions. Nevertheless, some excessive cement paste is found to be attached to the larger aggregate fractions and angular aggregates are produced in the smaller fractions.

Further analysis is required on the mineralogical composition of the aggregates produced, validating the quality of the separation. Next to that, an optimisation study of the process is needed in the future.

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