Dynamic compaction of crushed concrete fill, full-scale test at Jätkäsaari, Helsinki

S Anttila1, J Forsman1, K Rantala2, T Dettenborn1, M Suominen2, J Lehtonen3

1 Ramboll Finland Oy, Itsehallintokuja 3, 02601 Espoo, Finland
2 City of Helsinki, 00099 Helsingin kaupunki, Finland
3 Turku University of Applied Sciences, Joukahaisenkatu 3, 20520 Turku, Finland

sanna.anttila@ramboll.fi

Abstract. Concrete waste in the form of crushed concrete can be utilized in street and road structures. Today, a significant amount of concrete waste generated by various demolition and other activities is not fully utilized in infrastructure projects within Helsinki; as a result, a portion of concrete waste generated in the city is transported to other sites outside the Helsinki metropolitan area. In Helsinki, large-scale land reclamation projects have been implemented, and this trend will continue in the near future. Utilization of concrete waste as fill material in land reclamation projects will reduce the need to transport concrete waste outside the Helsinki metropolitan area, with a concurrent reduction in need to transport blasted rock to the land reclamation sites. This will promote reuse and recycling of waste and will reduce heavy traffic and CO2 emissions. Crushed concrete has not been previously tested in Finland as a fill material in land reclamation projects subjected to deep compaction methods. In 2018-2019 suitability of crushed concrete for land reclamation purposes was tested in a full-scale dynamic compaction test. The objective of the test was to assess the degree of compaction produced by dynamic compaction, determine the compression rate of compacted layers under pre-loading embankment, and measure environmental impacts of the fill material. The pilot structure was implemented in Tritoninpuisto (Triton Park) located in the southern part of Jätkäsaari. Crushed concrete with varying grain size was compacted using the dynamic compaction method. All materials compacted well. Results of the pilot study indicate that dynamic compaction can be applied to densify crushed concrete fill material for land reclamation. Settlement plates on the top and the bottom of the pilot structure were used to monitor short-term settlement during dynamic compaction and long-term settlement after completion of the work. Long-term settlement was minor after compaction and placement of a pre-loading embankment. Implemented study has indicated that compacted crushed concrete is a suitable material for land reclamation in street and park areas.

1. Introduction
Approximately 1 million tons of concrete waste is generated annually in Helsinki Finland metropolitan area by various demolition sites, and the entire amount cannot be utilized in infrastructure projects located there. As a result, a portion of the concrete waste generated within the city limits is transported to construction sites outside the city, sometimes located at considerable distance.

In Helsinki, large-scale land reclamation projects have been implemented and the same trend is expected to continue in the near term. Until recently, blasted rock obtained from tunneling and rock ex-
Cavitation sites have been a preferred material for land reclamation applications; this material is commonly sourced both from within the city limits and from further afield.

Use of recycled crushed concrete can be considered as a replacement for blasted rock aggregates. To utilize recycled crushed concrete, a separate environmental permit is required for its use as a fill material in land reclamation projects. Due to significant presence of concrete dust and its tendency to float and/or create sludge fines that drift to sea, the land reclamation area must be bounded with lateral embankments and/or silt curtains. Further, the final structure must incorporate adequate slope erosion protection measures [1]. Utilization of concrete waste as fill material in land reclamation projects reduces the requirement to transport concrete waste from Helsinki metropolitan area and correspondingly decreases the demand for blasted rock, which is suitable for many other purposes. Additionally, reuse of crushed concrete in land reclamation applications promotes reuse and recycling of waste, reduces construction costs, and reduces project carbon dioxide emissions.

Crushed concrete was previously applied as a land reclamation material in certain park grading and filling projects in Helsinki. However, it has not been tested earlier in Finland as a structural fill layer placed into the sea and compacted using dynamic compaction technique in the location of a future street or another infrastructure project.

The City of Helsinki tested crushed concrete suitability in 2018-2019 for land reclamation material purposes in a full-scale dynamic compaction test performed in Tritonpuisto (Triton Park) located in Jätkäsaari area (figure 1). The pilot structure included blasted rock and crushed concrete of three gradations: crushed concrete #0/90mm, crushed concrete #0/150mm, and crushed concrete #0/300mm. Compaction rate and settlement of the crushed concrete fill sections was compared to the blasted rock fill reference. Short-term settlement of crushed concrete layers caused by compaction, and long-term settlement generated by a pre-loading embankment were studied during the test. Environmental impacts of the applied material were also investigated. Additionally, changes in grain size distribution and unit weight caused by compaction were observed and measured. Material compaction rate and long-term settlement are considered the most relevant geotechnical properties when considering applicability of the material for fill purposes.

![Figure 1. Location of pilot structure in Jätkäsaari area [2].](image-url)
2. Compaction test

2.1. Location and soil conditions in test area
The pilot structure was implemented in Tritonpuisto (Triton Park) located in the southern part of the Jätkäsaari development area reclaimed from the sea in 2010 and filled with blasted rock.

The thickness of the blasted rock fill is approximately 13m. A clay unit present in accounted reclaimed area prior to construction was dredged to prepare the seabed for filling. The seabed subgrade after dredging consist of gravelly, silty and stony sand. The pilot structure is situated approximately 12m from the shoreline. Soil conditions in the area are presented in the cross section in figure 2.

Groundwater level at the pilot location fluctuates relative to the sea level. In 2019, theoretical mean water in Helsinki was approximately +0.2m relative to the N2000 vertical datum [3].

![Cross-section of a pilot test area](image)

**Figure 2.** Cross-section of a pilot test area. [4].

2.2. Pilot structure dimensions and materials
The pilot structure was constructed within an area that had previously been filled with blasted rock. Preparation of the pilot structure commenced with an excavation measuring 40m × 7m × 5m (length × width × depth) in the existing compacted rock fill. The pilot structure was divided into four zones. In three zones, crushed concrete with varying gradation (#0/90mm, #0/150mm and #0/300mm) was placed, and the fourth zone was filled with blasted rock (#0/300mm). Fill was placed approximately 3.5m below groundwater level (-3.5m elevation). Dimensions of the pilot structure and location of various fill materials are shown in figure 3.

Samples of crushed concrete were taken during fill placement to determine grain size distribution of the material. A grain size distribution curve of crushed concrete with gradation #0/90mm prior to deep compaction is shown in figure 4. The pilot structure was implemented using crushed concrete with rather large grains. Getting representative samples of the material with gradation #0/150mm and #0/300mm would require substantial sample amounts. Since the objective was to obtain a general picture of the material grain size distribution, sampling in accordance with the standard requirements was not considered necessary because of laborious maintenance, handling and testing of samples. Thus, the representativeness of the samples may not be good due to the emphasized importance of a separate piece/grain.
Based on visual inspections, crushed concrete included substantial amount of fine-grained material. Steel debris, large single pieces and whole brick were observed in crushed concrete with gradation #0/300mm. Crushed concrete applied in the deep compaction test are shown in figure 5.

**Figure 3.** Pilot structure dimensions and test zones [5].

**Figure 4.** Grain size curves of crushed concrete #0/90mm.

**Figure 5.** a) Crushed concrete #0/90mm, b) #0/150mm and c) #0/300mm.
2.3. Measurements and instrumentation
Settlement was monitored during the short-term (deep compaction operation) and long-term (after densification) using settlement plates equipped with reference rods and installed into the pilot structure. Settlements were determined by periodically measuring the elevation of the top of the reference rods. Each test zone was outfitted with two settlement monitoring plate sets, located at bottom level of the fill (approximately -3.5m), groundwater level (approximately +0.9 - +1.0m), and top level of the fill (approximately +1.5 - +1.6m). The settlement plate placed at the base of the fill area allowed determination of settlement of the underlying rock fill unit left in place beneath the test section. Principle arrangements of the settlement plates and tubes are shown in figure 4.

Compaction rate of the fill during the work was estimated by measuring the settlements in the fill surface caused by the impact of the compaction weight. Samples to determine the compressive strength of crushed concrete and changes in the material grain size distribution caused by dynamic compaction were studied in a laboratory.

In connection with the dynamic compaction test, a separate environmental study was performed to estimate the environmental impacts of the applied crushed concrete. For purposes of the study, groundwater samples were taken from piezometers installed in the pilot structure and its vicinity, and surface water samples taken from the sea. Findings of the environmental study are outside the scope of this paper.

2.4. Performance of compaction test
Prior to the construction of the pilot structure, the existing blasted rock embankment was compacted using dynamic compaction method to eliminate potential settlements and lateral displacements that may occur below and around the pilot structure during the test. This operation was intended to minimize outside effects on the performance of the materials during the pilot study.

To measure the settlements in the bottom of the pilot structure, settlement plates and tubes were installed on the bottom of the excavation made in the rock fill. Installed settlement plates equipped with the reference rods and settlement tubes are presented in figure 5.

![Figure 6. Principle arrangements of settlement plates and tubes presented in cross section [6].](image-url)
The excavation was then filled in two stages. The first layer of fill material was placed to the level of the prevailing groundwater (+0.9 - +1.0m) and a set of settlement plates was installed. Subsequently, the second fill layer was completed to final level of +1.5 - +1.6m corresponding to the surrounding ground surface. Above the fill structure, 0.3m thick cushion layer was placed. Dynamic compaction was performed on the fill mass with the settlement plates installed as noted, and upon completion of dynamic compaction the surface monitoring plates were installed. For long-term settlement monitoring purposes, a pre-loading embankment was placed on the test structure.

Dynamic compaction of blasted rock and crushed concrete composing the pilot structure was designed in accordance with dynamic compaction of blasted rock fill performed previously in the area. Compaction depth impact was designed to reach the depth of 8m, i.e. 3m below the bottom of the pilot structure [7]. The depth impact was determined empirically using so-called Lukas equation [8] (equation 1). Total energy required for the compaction was calculated using equation 2 [8].

\[
D = k\sqrt{(W*H)} \tag{1}
\]

where

- \( D \) = compaction depth impact [m]
- \( k \) = empirical factor (< 1) [-]
- \( W \) = tamper mass [t]
- \( H \) = drop height [m]

\[
EA = \frac{N \cdot W \cdot H \cdot P}{d^2} \tag{2}
\]

where
EA = total energy per unit area [kJ/m$^2$]  
N = number of drops in compaction round [unit]  
W = tamper mass [t]  
H = drop height [m]  
P = number of compaction rounds [unit]  
d = drop spacing [m]

Compaction energy required for soil with high hydraulic conductivity shall be approximately 200-250kJ/m$^3$ [8]. Compaction energy designed for the pilot structure was 230kJ/m$^3$. On the site, a lighter weight was applied (compared with the designed) and drop height was increased correspondingly so that actual compaction energy was equal to 222kJ/m$^3$ which is considered sufficient for blasted rock compaction. Total energy applied in dynamic compaction and parameters used to determine the energy are shown in Table 1.

Table 1. Design parameters of dynamic compaction for blasted rock and total energy per compaction unit volume [7].

| Parameter                              | Value              |
|----------------------------------------|--------------------|
| Weight                                 | 11 t               |
| Drop height                            | 10.5 m             |
| Thickness of fill layer                | 13 m               |
| Empirical factor k                     | 0.75               |
| Number of compaction rounds            | 4 rounds           |
| Number of drops in compaction round    | 3 drops / point    |
| Drop spacing                           | 2.5 m              |
| Square area                            | 6.25 m$^3$         |
| **Compaction energy**                  | **222 kJ/ m$^3$**  |

The dynamic compaction project was performed using a lattice boom crawler crane and a cylinder shaped weight with a diameter of 1.7m. Drop spacing on a square grid pattern was 2.5m. The weight used was 11t and drop height 10.5m. All together 4 compaction rounds were made with 3 drops at each point. Settlements formed in the fill surface after the first compaction round are shown in figure 6.

Figure 8. Settlements formed in fill surface after first compaction round (Credits: Anttila 4.4.2019).
3. Results

Based on the settlement plates installed on the groundwater level (+0.9 - +1.0m), compression caused by dynamic compaction was approximately 160-190mm in blasted rock fill areas and approximately 200-400mm in crushed concrete fill areas. Maximum compression of the fill was detected during dynamic compaction work. Minor settlements occurred after dynamic compaction. After construction of a pre-loading embankment that followed the compaction test, settlement monitoring was focused on long-term settlement. Compared to the measurements made immediately after the dynamic compaction project, differences in elevations measured in 6 months were ±3mm. Long-term settlement in test zone 2 (fill material crushed concrete #0/150mm), are shown on a time-settlement diagram in figure 7. Based on 6 months monitoring of the settlement plates installed on top of the fill, settlement at the fill surface have been within 3 mm range from zero-measurement. In the calculations of fill compression, settlements in the blasted rock fill below the pilot structure were notified. Observation was made based on measurements from the settlement plates installed on the bottom of the pilot structure. Settlement in the bottom of the pilot structure measured during dynamic compaction varied from 0 to 20mm. Afterwards, changes in elevations were rather minor (-1 - +4mm).

![Figure 9](image.png)

**Figure 9.** Settlements monitored from settlement plates installed on groundwater level (+0.9 - +1.0m) in test zone 2 (crushed concrete #0/150mm)

There were no significant differences in compaction rate of various fill materials during dynamic compaction. The work quality was controlled by monitoring the total value of settlement generated by two last drops. As expected, an upper limit of maximum 100mm settlement measured for the last two drops was specified as the acceptance criteria and was achieved at most of the points in the fourth compaction round. In some separate points, required settlement criterion was exceeded. In these points, total settlement of two last drops varied from 110mm to 140mm. Considering location of the points throughout the pilot structure, the material type did not have a significant effect on the total settlement value of two last drops. Total settlement value in the blasted rock fill area measured between 340mm and 1190mm. Total settlement in areas filled with crushed concrete #0/300mm ranged from 540mm to 1370mm. Total settlement in areas filled with crushed concrete #0/150mm ranged from 380mm to 1150mm. Total settlement in areas filled with crushed concrete #0/90mm ranged from 438mm to 980mm.

Dynamic compression modulus was determined by measuring the deceleration of the weight at the moment of impact and related stress and settlement dependency. Due to disturbances occurred during the measurements, dynamic modulus values varied significantly between different points but altera-
tions in calculation results performed based on the measurements are similar in different test zones. In general, increased number of drops in all test zones resulted in the increased dynamic modulus.

The degree to which the crushed concrete was pulverized by dynamic compaction was studied by separate samples taken prior to and after the compaction work, to provide random results. However, according to the grain size distribution analyses, grain crushing in the crushed concrete did not have a harmful influence on performance of the finished structure. Because of incorrect measurement results, the influence of dynamic compaction on material unit weight was not studied in connection with the compaction test.

Compression strength of samples studied in a laboratory for 28 days duration test was more than 0.8MPa (ϕ100mm×h100mm cylinder samples). Therefore, the material meets the compression strength requirements set by the guidelines for use of crushed concrete in municipal construction projects. Specimens for the compression test were prepared by screening samples in 22.4mm sieve according procedure guide for laboratory tests [9]. In the test, reduction of compressive strength was observed in materials with larger grains as follows: 1.2MPa for crushed concrete #0/90, 1.0-1.1MPa for crushed concrete #0/150, and 0.9MPa for crushed concrete #0/300.

According to the results of environmental monitoring performed until the end of 2019, impact of crushed concrete on groundwater and surface water is very localized. Based on samples taken from the piezometers installed in the pilot structure, level of pH in groundwater was clearly increased, but the pH of seawater has remained the same. Detailed results and assessments of the environmental study will be finalized in a separate report in the end of 2020.

4. Conclusions

Dynamic compaction of crushed concrete in a land reclamation application was tested successfully, and the study included measurements to establish fill material characteristics essential to ensure acceptable compaction rate and geotechnical performance during and after the project. Long-term settlement of crushed concrete is the most relevant property to be considered in the performance of a street or other structure that shall be designed with limited total and differential settlement tolerance. The primary objective of the study was to define this characteristic of the material.

Based on the measurements from settlement plates installed at groundwater level (+0.9 - +1.0), settlements occurring in the crushed concrete fill areas were on average slightly larger than in the blasted rock fill area. Because settlement occurring during compaction is typically rectified with placement and grading of additional fill material, and the subgrade is subsequently leveled and graded once or several times prior to installation of road structural layers, short term settlement during compaction is non-critical for technical performance of the final structure.

Long-term settlements in the pilot structure monitored for 6 months following the compaction project have been minimal (in range of ±3mm) after construction of the pre-loading embankment. No further settlements are anticipated, because normally most significant settlements in dynamically compacted non-cohesive soil occur just after loads have been applied to the soil.

No significant differences in compaction rates of crushed concrete with various grain sizes and blasted rock fill were observed. Based on the measured settlements caused by a weight during the compaction work, compaction rates of crushed concrete and blasted rock in the pilot structure shall be confirmed as similar. No significant differences were observed in total settlement values of separate drop points located in various test areas. Moreover, based on the defined dynamic compression modulus, the compaction rate of crushed concrete was similar to blasted rock. Therefore, the dynamic compaction method can be considered suitable for compaction of the crushed concrete fill partially located below the groundwater level.

Because of insufficient number of samples and inconsistencies in obtained data, a reliable assessment of degree of particle pulverization caused by dynamic compaction cannot be assessed at this time. However, alterations in grain sizes distribution are presumably not significant for fill geotechnical performance.
According to the performed compaction test, crushed concrete (due to its geotechnical properties) can be considered suitable fill material to be applied in land reclamation projects in the location of parks and transport areas. Possibilities to use the material below buildings or structures in land reclamation projects have not been studied. The performed test structure can be used later for test piling with driven steel piles and pre-fabricated concrete piles, providing that current settlement measurements are continued for a sufficient period of time. The required duration of monitoring shall be estimated according to the results of futures measurements. Test piling using drilled piles may be challenging due to the presence of steel debris in crushed concrete. In the event that buildings and structures are allocated in the area filled with crushed concrete, design of foundations and performance of underdrains shall require detailed studies. Frost and salt related issues are not relevant for the crushed concrete fill placed below the frost penetration depth.

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