Recycling of concrete from demolished bridges and other engineered structures

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Abstract. The Environmental Policy (2014) of the Finnish Transport Agency (now the Finnish Transport Infrastructure Agency) identifies reducing the volume of waste and conserving renewable and non-renewable natural resources as one of the Agency’s environmental goals. The Agency has decided to pursue this goal by various means, including promoting the use of recycled materials, revising legislation and permit and notification procedures, and improving its purchasing practices and guidance. At the beginning of 2018, the Finnish Transport Agency was responsible for 15013 road bridges and 2516 railway bridges. Two thirds of the road bridges are made of concrete, and their total area accounts for approximately 80% of the total area of all road bridges in Finland. The Finnish Transport Agency currently has limited official guidance and few other established procedures for sorting and recycling concrete waste generated from the demolition of engineered structures in connection with road and rail projects. According to circular economy principles, demolition waste should be reused in a manner that adds the most value to the project and is utilized as close to its source as possible. Concrete waste from demolitions often ends up in secondary use such as embankment fills or noise barriers, which is not, from the perspective of the environment or the economy, the most optimal way to use the material. Concrete waste crushed down to the correct size, the resulting crushed pieces make a high-quality construction material. High quality crushed concrete can be used in accordance with the registration procedure set out in the Government Decree on the Recovery of Certain Wastes in Earth Construction or, if the project and/or the material do not satisfy the requirements of the Government Decree, in accordance with the environmental permit procedure. Bridge demolition concrete waste should ideally be treated and processed to add as much value to projects as possible. Pulverisation is relatively expensive and the end product has a relatively low value, which is why, in practice, it almost always makes sense to reduce concrete waste down to, for example, a size that satisfies the quality requirements for the sub-base set out in the Government Decree on the Recovery of Certain Wastes in Earth Construction in a crushing plant or using a crusher bucket.

1. Introduction

Reduction of waste volume and economical use of renewable and non-renewable natural resources is one of the most important environmental goals set by the Finnish Transport Infrastructure Agency (FTIA) in its Environmental Policy [1]. To achieve this goal, the Agency has decided to promote the use of recycled materials, to revise legislation and permit and notification procedures and to improve its procurement practices and guidance.

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Priority of measures preventing waste generation and waste management hierarchy are provided in Directive 2008/98/EC of the European Parliament and of the Council [2]. In the priority order determined by the Directive, arrangements preventing waste generation shall be followed by measures preparing the waste for re-use, and further followed by recycling. The directive (EU waste framework directive from 2008) requires member states to recycle 70 per cent of their construction and demolition waste as material by 2020. In 2018, the Finnish Government approved the National Waste Plan that presented measures to be performed to 2023 and long-term targets to 2030 for waste management and prevention. Regarding construction waste, the approved measures include the guidelines for the public sector on material efficiency and recycling in new construction, renovation and infrastructure projects.

According to the principles of circular economy, demolished concrete waste shall be reused or recycled at the highest possible rate and as close to the source of its origin as possible. In the waste hierarchy, utilization of crushed concrete waste can reach the highest level only when it is converted into stone aggregate material meeting all technical requirements set to the standard product.

Currently, the FTIA has very limited guidelines and few other established procedures for sorting and recycling concrete waste from the demolition of engineered structures in connection with road and rail projects. In 2000, the Finnish Road Authority published the guidelines [3] for design and construction using crushed concrete waste. Later, these guidelines were adjusted by various parties including Finnish Road Administration, Transport Agency, cities and industries. The utilization of crushed concrete aggregate has started in yearly 1990’s and some of the roads from that time are still under monitoring [4]. Since 2006, a notification procedure [5] (notice, update in 2017) has been applied for using crushed concrete in earthworks. In 2017, InfraRYL [6] instructions were supplemented with crushed concrete quality requirements and construction guidelines. Most recently, the quality management standard of crushed concrete [7] refining published in 2001 was updated in 2018.

The objective of the current study was to collect together all data on bridges and engineering structures managed by the Finnish Transport Infrastructure Agency and the amount of concrete they contain. Another objective was to describe concrete waste handling and refining procedures on demolition sites. Collected data was used to evaluate the cost-effectiveness of handling, refining and utilization of the concrete waste (from demolished bridges of various sizes) compared with the handling at treatment facilities.

2. General information about concrete bridges of FTIA
At the beginning of 2018, the FTIA was responsible for 15013 road bridges and 2516 railway bridges [8]. In Finland, bridge construction was quite extensive in the 1960s, when the amount of bridges by surface area constructed nearly tripled compared with the previous decade. The bridge construction market continued growing until the end of 1990s’, and at the beginning of 2000s’ a considerable number of new railway bridges were built. In 2017, 77 road bridges and 11 railway bridges were completed. Bridge and other engineering structure data have been saved in the Register of Engineering Structures, which replaced the Bridge register in 2017.

Two thirds of the road bridges are made of concrete, and their total area accounts for approximately 80% of the total area of all road bridges in Finland. Most concrete bridges are made of reinforced concrete slabs. A higher percentage of railroad bridges are concrete in comparison with road bridges. Concrete bridges represent approximately 80% of all railway bridges, and their area accounts for 84% of the total area of all railway bridges.

3. Volume of concrete in bridges
For purpose of the study, material consumption tables maintained by the Finnish Road Administration [9] were combined with the material consumption tables presented by Tahvola [10]. Table data were used to estimate the size rates of average bridges and related demolition costs. Material consumption data are mostly based on bridge data forms. Contents of the bridge data form are presented in “Designs of bridges” publication by the Finnish Road Authority [11].
The material consumption table by the Finnish Road Administration [9] covers beam bridges, slab bridges and box girder bridges built in 1992-2002. The material consumption table prepared by Tahvola [10] presents reinforced concrete road bridges built in 2003-2016 and managed by various municipalities. The combined material consumption table (table 1) includes all together 693 bridges.

Bridges with the largest volume of concrete are prestressed box girder, slab and beam bridges. Volume of concrete in bridges estimated from the combined material consumption table is shown in figure 1. The diagram and average (appr. 540 m$^3$) and median (390 m$^3$) ratio indicates that most of the bridges are small-size structures.

Table 1. Statistical indicators of concrete volume by bridge types presented in combined material consumption database [9,10]

| Volume of concrete, m$^3$ | count | mean  | std   | min  | 25 % | 50 % | 75 % | max  |
|--------------------------|-------|-------|-------|------|------|------|------|------|
| Prestressed box girder bridges | 5     | 2348  | 2480  | 507  | 838  | 1525 | 2250 | 6620 |
| Prestressed slab bridges  | 5     | 892   | 426   | 174  | 923  | 974  | 1100 | 1290 |
| Prestressed beam bridges  | 23    | 992   | 555   | 335  | 532  | 895  | 1314 | 2353 |
| Multi-span prestressed beam bridges | 84 | 1025  | 711   | 101  | 510  | 822  | 1241 | 4529 |
| Continuous prestressed beam bridges | 91 | 769   | 597   | 220  | 436  | 588  | 841  | 3675 |
| Continuous slab bridges  | 137   | 572   | 353   | 87   | 369  | 497  | 653  | 2924 |
| 2-span prestressed beam bridges | 79 | 502   | 244   | 213  | 322  | 393  | 639  | 1280 |
| Single-span cantilever bridges | 52 | 259   | 129   | 77   | 151  | 265  | 343  | 523  |
| Single-span prestressed beam bridges | 66 | 282   | 133   | 83   | 202  | 240  | 367  | 734  |
| Single-span slab bridges  | 56    | 223   | 84    | 93   | 156  | 234  | 278  | 441  |
| Prestressed pedestrian and bicycle bridges | 13 | 218   | 63    | 165  | 186  | 196  | 219  | 401  |
| Slab frame bridges        | 68    | 167   | 69    | 82   | 126  | 145  | 183  | 515  |
| Single-span composite beam bridges | 14 | 93    | 41    | 36   | 73   | 86   | 116  | 192  |
| Total                     | 693   |       |       |      |      |      |      |      |
Figure 1. Average volume of concrete in bridges estimated from combined material consumption table [9,10]

4. Cost effectiveness analysis
For purposes of calculation, it is assumed that refined concrete waste from demolished bridges will be applied in a road sub-base course. Concrete waste may be also converted into the material suitable for a base course. Principal impacts of the concrete waste refining and utilization on total costs are shown in figure 2.

For purposes of calculation, the in-place density of a concrete structure is assumed to be 2.4 t/m³, and bulk density of crushed concrete is assumed to be 2.0 t/m³. Other costs applied in the analysis are shown in table 2. Transportation distances in the table above selected for the analysis are estimated based on availability of stone aggregate in the project area and location of the concrete waste treatment facilities. In addition to the size of concrete fragments, reception fee varies by locations of treatment facilities.
Figure 2. Principles of cost impacts by concrete waste refining.

Table 2. Cost data applied for analysis.

| Cost factor                        | Quantity | Unit       |
|------------------------------------|----------|------------|
| Concrete waste treatment and refining |          |            |
| Concrete waste reception           | 20       | €/ton      |
| Crushing, horizontal shaft impact  | 10       | €/ton      |
| crusher (sub-base layer)           |          |            |
| Crushing, jaw crusher (embankment fill) | 7.5    | €/ton      |
| Crusher mobilization               | 2500     | €/set      |
| Laboratory tests, embankment fill  | 2500     | €/set      |
| Laboratory tests, base/sub-base course | 4500  | €/set      |
| Transportation cost                |          |            |
| Transportation (5-10 km)           | 4.5      | €/ton      |
| Transportation (10-15 km)          | 6.0      | €/ton      |
| Transportation (15-20 km)          | 7.5      | €/ton      |
| Transportation (20-25 km)          | 10       | €/ton      |
| Transportation (> 50 km)           | 15       | €/ton      |
| Construction                        |          |            |
| Stone aggregate, material (embankment) | 4.0    | €/m$^3$ theoretical |
| Stone aggregate, material (sub-base course) | 11    | €/m$^3$ theoretical |
| Construction (crushed concrete and stone aggregate) | 4.0   | €/m$^3$ theoretical |
A case of concrete waste refining impacts on project costs is presented in figure 2 and table 3. In this case, 400 m$^3$ of concrete waste from a demolished bridge (average size) is handled and refined on site (within the project) and produced material is applied in a sub-base course. Cost estimate of this stages is approximately 18 500 €.

Corresponding cost estimate for the project performed in a conventional way when demolition waste is transported to a waste treatment center and comparable amount of natural stone material is delivered to the site, is approximately 32 900 €. Most significant expenses avoided are fees associated with the concrete waste disposal to a landfill. Typically, concrete waste reception fee depends on the location of the treatment facilities and sizes of concrete fragments.

![Figure 3. Cost impact of concrete waste refining to sub-base material.](image)

**Table 3.** Cost impact of various stages of concrete waste refining (for figure 3).

| Parameter                          | Quantity | Unit     | Not utilized [€] | Utilized [€] |
|------------------------------------|----------|----------|------------------|--------------|
| Bridge size                        | 400      | m$^3$    |                  |              |
| Volume of crushed concrete         | 480      | m$^3$    |                  |              |
| 960 [ton]                          |          |         |                  |              |
| Reception fee                      | 20       | €/ton    | 19 200 €         | -            |
| Transportation of concrete waste   | 7.5      | €/ton    | 3 600 €          | -            |
| (15-20 km)                         |          |         |                  |              |
| Stone material (sub-base course)   | 11       | €/m$^3$  | 5 280 €          | -            |
| Transportation of stone material   | 6.0      | €/ton    | 2 880 €          | -            |
| (10-15 km)                         |          |         |                  |              |
| Crushing by impact crusher (sub-   | 10       | €/ton    |                  | 9 600 €      |
| base course)                       |          |         |                  |              |
| Crusher mobilization               | 2 500    | €/set    |                  | 2 500 €      |
| Laboratory tests, sub-base course  | 4 500    | €/set    |                  | 4 500 €      |
| Construction                        | 4.0      | €/m$^3$  | 1 920 €          | 1 920 €      |
| **Total**                          | **32 880 €** | **18 520 €** |               |              |
Cost differences associated with using concrete waste vs. natural stone material are shown in figure 4 and 5. Figure 4 presents results for volume of concrete in the demolished structure is less than 500 m$^3$ which corresponds to more than half of bridges in Finland (according to the performed analysis shown in figure 1). Results of respective calculations for the bridges with volume of concrete equal to 500-4000 m$^3$ are provided in figure 5. For purposes of calculation, the distance of concrete waste transportation is estimated to be 15-20 km, and the distance for transportation of stone material is assumed to be 10-15 km, because the stone quarry area is probably located closer to the site than the waste treatment center. Other parameters used in the calculations are presented in table 2.

Figure 4. Impact of concrete volume in demolished bridge on cost effectiveness of concrete waste utilization in project. Volume of concrete in bridges varies between 150 and 500 m$^3$.

Figure 5. Impact of concrete volume in demolished bridge on cost effectiveness of concrete waste utilization in project. Volume of concrete in bridges varies between 500 and 4000 m$^3$. 
Based on the calculations presented in figures 4 and 5, it can be concluded that it is more profitable to crush, refine and utilize concrete waste for the construction (as embankment fill or sub-base course material), than to transport concrete waste to the treatment facilities and use the corresponding amount of the natural stone material. This concerns even less than 200 m³ concrete bridges.

5. Summary
A theoretical calculation model developed in the study indicates that utilization of concrete waste from demolished bridges may provide significant cost savings for the project. Based on interviews, concrete waste crushing and recycling on the demolition site is almost always feasible providing that preconditions for that have been considered on the project planning stage.

To promote recycling, studies of environmental acceptability, quality, application and treatment facilities of concrete waste may be performed prior to the construction. For example, environmental acceptability of concrete in a given bridge may be studied from samples taken during the bridge condition assessment.

Concrete waste from demolished bridge is recommended to process to the highest possible degree. Crushing concrete waste to small grains in crushing equipment or jaw crusher is the most reasonable solution, because powdering costs are quite high, while final product price is low. One possible product can be e.g. crushed concrete class II which corresponds to sub-base material and MARA requirements.

The notification procedure may be applied in road and field structures and subgrades for industrial and storage buildings. In these applications, maximum permissible grain size of crushed concrete is 90 mm. Planned utilization of crushed concrete with larger grain size requires a separate environmental permit or small-scale application permit from local environmental authorities.

Application and use of crushed concrete in road pavement or fill structures shall be approved by the client. Respective structural analyses and calculations of crushed concrete shall be performed by a designated structural engineer.

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