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Application of Crushed Concrete in Geotechnical Engineering – Selected Issues

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Abstract. The reuse of building materials becomes an important issue in sustainable engineering. As the technical requirements for civil engineering structures changes with time and the life time is limited, the need of building new objects meets the necessity of recycling of the existing ones. In the case of steel structures, the possibility of recycling is obvious, also in the case of wooden constructions, the possibility of "burning" solves the problem. The concrete waste is generated mainly as a result of the demolition and reconstruction of residential and industrial buildings. These types of waste are basically made from crushed rocks and cement minerals and contain non-hydrated cement particles in its composition. Concrete poses a lot of problems mainly for two reasons. It is difficult to crush, heavy and hard to transport and demanding in reuse. Different fractions (particle sizes) may be used for different purposes. Starting from very fine particles which can be used in concrete production, through regular 16-300 mm fractions used to form new fills and fill the mats, up to very irregular mixtures used to form stone columns by means of Impulse Compaction or in Dynamic Replacement. The presented study juxtaposes authors experience with crushed concrete used in civil engineering, mainly in geotechnical projects. Authors' experiences comprise the application of crushed concrete in the new concrete production in Russia, changing pulverized bridge into the fill of mesh sacks, or mattresses used as an effective way to protect the shoreline and the New Orleans East land bridge after Katrina storm (forming a new shoreline better able to withstand wave actions), and finally the use of very irregular concrete fractions to form stone columns in week soils on the example of railway and road projects in Poland. Selected case studies are presented and summarized with regard to social, technical and economic issues including energy consumption needed for proposed technologies and dynamic impact of ground transmitted vibrations and noise.

1. Introduction – the need for the reuse of building materials

The usage of recycled crushed concrete aggregate produced by crushing of concrete waste may not only reduce the consumption of natural aggregate, but may reduce the amount of concrete waste that ends up in landfills as well. Depending on the method of grinding, the concrete waste may have different properties which make it optimal for use in certain materials [1]. The crushing and screening process at the screening plants (figure 1) produces fine recycled concrete aggregate (with particle size less than 5 mm) and coarse recycled concrete aggregate (with particle size more than 5 mm). There were a lot of studies of fine recycled concrete aggregate [2-3] and coarse recycled concrete aggregate [4], which shows that these aggregates could be used as a replacement for natural aggregates in composing of decorative [2] and structural concrete [3] and in granular fill construction [4].

Figure 1. Crushing and screening of concrete waste elements (courtesy Keller Polska)

2. The application of various fractions – comments and selected case studies

Various researchers have proved that the use of crushed concrete of a fraction of 5-40 mm is possible in reinforced concrete and concrete products. It is assumed that the application up to 30% of the mass of a coarse aggregate can be done without any special preparations as the technologies for the use of this aggregate had been already developed. Other research has been conducted on the application of fine recycled concrete aggregate in structural and high performance concrete. Simultaneously, numerous geotechnical technologies make it possible to use qualified and even unsorted crushed concrete (or spoil rocks from coal mines) in the construction of roads [4], in soil improvement (stone columns formed by vibro or dynamic replacement) or simply by means of steel gabion or polymer mattresses filling. The last mentioned technology – the use of marine mattresses, which are rock-filled containers built with advanced ultra violet (UV) stabilized co-polymer geogrid materials, is more and more popular in coastal regions. These panels are laced together to form mattress-shaped baskets, similar to steel gabions, and are filled with natural stones or recycled concrete aggregates that form a protective layer against erosion and scour. The presented case study provides some basic information about New Orleans landbridge crushed and used to fill marine mattresses. It must be underlined that such use of crushed concrete is “ecological” in a double way: it reduces the amount of spoil material to be stored and may reduce the environmental cost of natural stone transportation to the building site.

2.1. Fine particles – decorative concrete

The questions of usage of crushed concrete fines as filler for fine grain concrete, aerated and foam concrete products as well as technological solutions for the production of paving tiles on crushed concrete aggregates were already worked out. Authors experience are based on studies and research program at Moscow State University of Civil Engineering, devoted to the questions of usage of crushed concrete fines from concrete scrap for the production of high-quality decorative composite materials based on mixed binder. It was proved [3] that crushed concrete fines may have a positive impact on the structure of the concrete matrix and could improve the environmental and economic characteristics of the concrete products. Dust fraction of crushed concrete fines contains non-hydrated cement grains, which can be opened in screening process due to the low strength of the contact zone between the hydrated and non-hydrated cement. In addition, the screening process could increase activity of the crushed concrete fines, so it can be used as a fine aggregate and filler for concrete mixes. The application of fine particles may however require some attention concerning water absorption [5] and workability. These problems can be solved by means of superplasticisers, [6].

2.2. Mixed sort of particles – from ashes to gravels

As the result of crushing process – various grain sizes may be obtained. Typical challenges concerning the application of anthropogenic soil, based on recycled concrete aggregate technology, were given in work [7] where mainly compaction problems were deeply analyzed.

Figure 2. Storage plant of crushed concrete waste at construction site (courtesy Keller Polska)

2.3. Large grains – filling of mattresses or *gabions*

Some interesting remarks based on selected case studies of application of marine mattress were given by Fiske [8], but one of the cases deserves deeper explanation. Nearly 45 bridges sustained damage in Alabama, Louisiana and Mississippi during Hurricane Katrina in fall 2005. In discussed case 7.5 mile, long twin-span bridge located at Lake Borgne that was destroyed during Hurricane is considered. This lake opens into the Gulf of Mexico and is subject to extreme tidal fluctuation during major storm events. The 2005 storm surge lifted the concrete spans from the support piles of the bridge. Many spans were dislodged and fell either completely or partially into the water. Seize of damages made no sense for repair works and decision for dismounting of whole bridge was taken.

Figure 3. Crushing and screening of bridge elements (courtesy Tensar International)

As shoreline protection is very important for region also another decision to construct geogrid marine mattresses along cost filled with crushed concrete from bridge was taken. Components of destroyed bridge were delivered via barge and stockpiled on site. Next crushing and screening went also on site. Construction with finally include over 84,000 cubic yards of concrete debris recycled from demolition of bridge was executed. During construction access to the site also was an issue. Because no construction equipment was allowed on the shoreline, all of the mattresses were filled offsite and placed onto a barge that brought them to the shoreline. Two barges, one materials barge loaded with 67 mats and one service and equipment barge. The crew lives on the barge for 11 days, working 12-14 hours per day before taking 3 days off. For this project owned by State of Louisiana, finally total of approximately 7,500 mats were installed. Installation was completed by January 2013 and since then there is no information about any problem with erosion ion section protected by Marine mattresses all are performing to expectations. Not only are these mats an effective way to protect the shoreline - they are also extremely cost-effective. Typically, the mattresses are 5' wide and 12" thick (nominal dimensions) with lengths varying up to 35'. Mats are available 18" and 24" thick although the length of the thicker mats is limited to 24' and 17' respectively. Max unit weight for a Triton Marine Mattress is 7.87 tons (15,700 lbs). All of the mechanical connectors (braid for lacing and bodkins for securing the baffles in place) are made of HDPE. All of the geosynthetics contain a minimum 2% concentration of carbon black to prevent UV degradation. Geogrids have been subjected to various independent tests for UV resistance.

Figure 4. Marine mattresses filled on site with crushed concrete (courtesy Tensar International)

Figure 5. Marine mattresses installed from barge (courtesy Tensar International)

Figure 6. View on completed cost protection Marine mattress (courtesy Tensar International)

2.4. Unsorted crushed concrete grains in stone columns – Dynamic Replacement for embankment

Crushed concrete based soil improvement works, under the new railway line, were performed using Dynamic Replacement method. The new railway line of the total length of over 2 km, linked existing railways in the western part of Poland. The big part of the project required forming new embankment of varying height. Part of project had to be constructed on weak soils. The embanked width equalled to 15 m and the height (corresponding to the imposed stresses) reached the range of 2-3 m.

The preliminary geological report prepared for the design phase of the project was based on 7 mechanical drilling to the depth of 6.0 - 9.0 m. It revealed potentially risky soil conditions – mainly the presence of highly compressible organic soils. Preliminary design excluded the possibility of forming new fills (embankments) directly on those week layers. W wide range of ground improvement and strengthening technologies was considered according to actual ground-water conditions and the planned static and dynamic loads (stresses) under the railway embankments. Finally, in the presented case, the Dynamic Replacement method was proposed due to its simplicity, law cost and easy control of process efficiency. The material used for the replacement was a mix of medium and large grain crushed concrete with natural sand. For the proper and safe design of soil improvement, the new research program was undertaken. It consisted of 7 additional mechanical drillings to the level 5-7 m below natural ground level, 3 cone penetration tests (CPTU test) to the depth of 7.8-11.8 m, 10 dynamic probing light (DPL) to the depth of 3,0-7,5 m and one dynamic probing heavy DPH to the depth of 12 m. Physical and mechanical parameters were evaluated both on the basis of laboratory tests and known correlations to the static penetration test results. The results were given in the form of soil profiles and geotechnical sections (figure 7), where all the soil layers were identified by the name and basic geotechnical parameters.

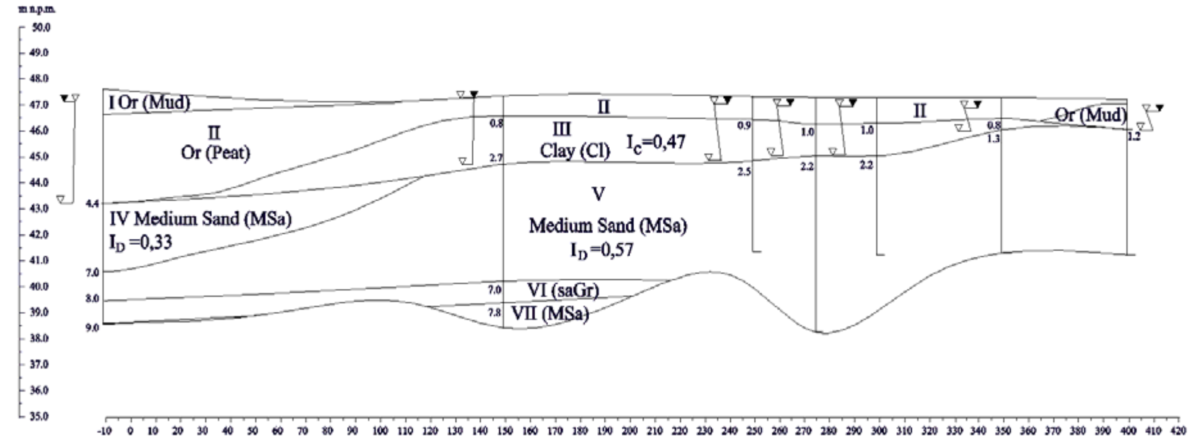

Figure 7. Geotechnical cross section in the longitudinal axis

The surface layer of week soils was identified as peats and mud. Its aggregate thickness varied from 1.2 m to 4.4 m. The layer was highly compressible with evaluated constrained modulus ranging from 0.16 MPa to 0.75 MPa. Undrained shear strength derived from tests equalled to 18 kPa. The organic soil was partially covering another soft plastic layer of non-organic clays represented by plasticity index I_c=0.47. The underlying non-cohesive soils, were represented in the upper layer by loose medium sand with density index I_D=0.33. The deeper layers were formed by medium dense medium sand with density index I_D=0.57. However the week soil thickness was not significant and could be replaced in most of the cases, the high level of measured ground waters reaching over the ground (see Figure 7) imposed the necessity of other solutions. After the analysis, of types and states of weak soils, levels of groundwater and future loads from the embankment, the Dynamic Replacement method was chosen for the weak soil improving. It was assumed that designer stone (or crushed concrete columns) will significantly increase soil bearing capacity and stiffness and may simultaneously accelerate the consolidation of natural cohesive soils and as the result reduce the secondary consolidation.

The principles of Dynamic Replacement are based on simple mechanical impact driving of granular material by dropping of heavy barrel-shaped rammer [10]. The average number of blows is usually over a dozen for each point. The mass of rammer varies from 10 t to 25 t. Typical drop height reaches up to 25 m. The working platform must be prepared prior to soil improvement works, in order to provide safe operation of heavy crane weighting up to 50 t. The formation process starts from crater formation (see Figure 8) – the rammer is being released from maximum height. Next, the crater is backfilled by granular material (like crushed concrete) and subsequent blows of rammer drive the granular material to the desired depth. At this stage, the drop height is limited to provide a better control of the driving process. The whole procedure is repeated to reach the desired depth – energy of blows is consequently raised as the soil capacity increases. At the final stage of column formation, the energy is limited again in order to control the densification (compaction) of the column head. Working depths which can be achieved by this technology (Dynamic Replacement) reach up to 5-6 m and the diameters vary from 1.6 m to 4.0 m.

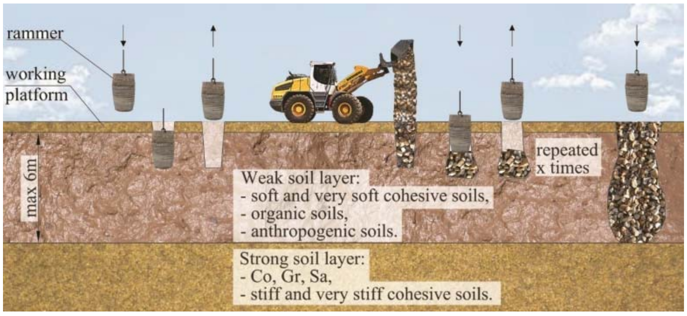

Figure 8. Process of column formation during the execution of dynamic replacement

Strengthening elements are usually concentrated under the transmitted loads. In the case of linear objects (roads, railways, river dikes), the columns are designed in regular patterns with the axis span of columns which is dependent on original soil conditions and the required resulting stiffness of the soil. In the presented case, assumed diameter of the column was 1.8 m and a triangular pattern of columns with the span of 3.0 m was proposed. Figure 9 illustrates actual technology details of Dynamic Replacement. Barrel-like shaped rammer weighting 9 t, was released from the maximum drop height of 15 m. After preliminary tests the drop height was reduced to 10 m in order to limit the dynamic impact on neighbouring (existing and operating) railway line (see figure 9 b). Reduced energy resulted with bigger number of blows reaching 20 for the majority of points (columns). The material used to form the columns was crushed concrete with sand, with particle fractions ranging 0-150 mm with the addition of natural sand. The same material was previously used to form a working platform.

a)  b) 

Figure 9. The dynamic replacement: a) the heavy crane with barrel-like shape rammer b) a material of column (crushed concrete with sand)

The quality checks of the columns (b means of excavation) confirmed, that the average diameter of the upper part of the columns reached up to 2.4 m. In the deeper parts, the resulting diameter of the columns equalled to 1.80 m (according to the preliminary design). The columns were based on the top of medium dense medium sand layer. After the completion of the works, some randomly chosen columns (one test for every 50 columns) were checked by means of static load plate tests. The testing plate diameter equalled to 1.05 m, and the loading devices (hydraulic jacks) were fixed against heavy crane. The stress range applied during the test varied from 0 to 200 kPa for the primary and secondary loading. The procedure of maintained constant load steps method was applied during entire test. The control of settlement was performed using standard electronic gauges based on independent reference beam fixed in a large distance from the loaded plate. The investigation proved that the primary deformation modulus of the columns reached in the most of the cases the value of 26 MPa. The corresponding deformation index equalled to I_0=2.3. A wide monitoring (maintaining) program started after the completion of the works and tests. The total settlement of the construction fill, measured after 3 months, reached just 1 cm with a clearly visible tendency to stabilization. It is worth emphasizing that the results generally confirmed the previous numerical modelling in the design phase based on former designers' experience [11-13].

2.5. Unsorted crushed grains in stone columns – Dynamic Replacement for bridge abutment

The case study described below is related to above mentioned problems with the dynamic impact of dynamic technologies [3]. The examination was carried out in 2009 and its dynamic impact on neighbouring structures was presented in works [15-16]. The object of investigation was the influence of soil improvement works under the planned high embankment for bridge abutment in southern Poland. The works related to Dynamic Replacement (see Figure 10) of natural organic soil were conducted in a similar way like in the previous case study. The only difference was the continuous control of vibrations. The monitored structures were: a building made in traditional technology and the foundation of bridge abutment under construction. The investigation did not reveal any symptoms of sensible negative impact of the vibrations.

The maximum level of vibrations (from the point of view of vibration speed) observed and recorded on both structures, at the final stage of each of the bridge columns formation, varied between 0.9 and 1.5 mm/s (Figure 11) and did not exceed the limits defined by the codes of practice as safe for structures. In the authors' opinion the reason behind those results is the considerable distance between the monitored structures and the source of vibrations.

Figure 10. The dynamic replacement - heavy crane with pipe-like rammer

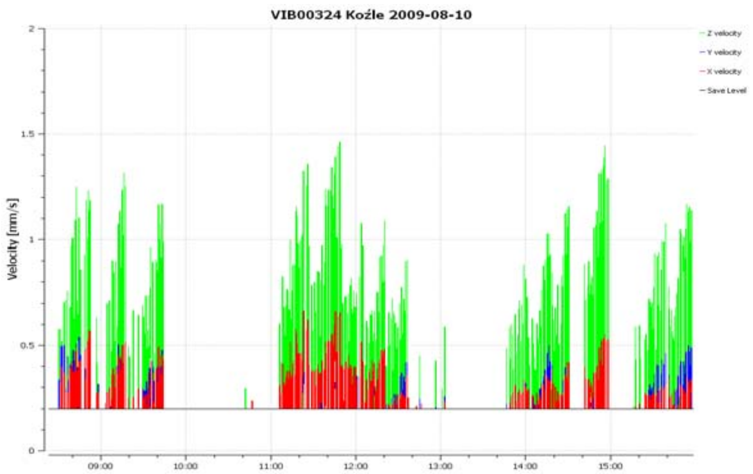

Figure 11. Velocity – Time graph (at residential house)

2.6. Unsorted crushed grains in stone columns –Rapid Impulse Compaction (RIC)
The technology of Rapid Impulse Compaction is similar to Dynamic replacement and is used mainly for the fast and efficient compaction of thick layers of granular fills. The hammer hits the steel plate of the 1.0 m diameter. When the crater is ready, the compactor changes its location and the crushed concrete is added. After a few cycles (usually 2-4 cycles) the roller is used to even the surface.

Figure 12. Equipment for Rapid Impulse Compaction (courtesy DABI)

The positive aspect of RIC is the possibility of using the irregular fractions of crushed concrete. The delivery of material can be seen on Figure 13. To obtain better compaction, the big boulders should be mixed with smaller size particles or simply with the sand or gravel.

Figure 13. Crushed concrete suitable for Rapid Impulse Compaction (courtesy DABI)

Rapid impulse compaction brings also many limitations concerning the dynamic impact on the surrounding structures, [17, 18]. Ground vibrations after each blow are transmitted through the soil body and especially by the ground water. Many case studies of such impact were already confirmed this phenomenon.

3. Discussion on advantages and limitations and conclusions
There are two groups of problems related directly to the proposed use of recycled concrete. In the case of new concrete production, no matter if it is just a decorative material or it needs a significant structural strength or durability, the use of porous particles or dust fractions impose the necessity of some special additives or treatment, [19]. The dust fraction of recycled concrete aggregate (particle size less than 0.063mm) is strongly unwelcomed in concrete technology. The main reason of this is very high specific surface which leads to high water consumption. Simultaneously, it influences water/cement ratio and, therefore, causes the negative impact on strength of composed concrete. Hydration water accumulates in porous structure of dust fraction particles and increases the amount of capillary pores in solid concrete.

The methods of lowering of influence of absorbed water are the constant interest of researchers. To achieve dense concrete structure with a little number of capillary pores, negative effect of dust fraction could be compensated by usage of superplasticizer. It could decrease the amount of water used to hydrate cement and the amount of water accumulated by porous structure. Thus, the usage of crushed concrete fines as fine aggregate in composition with polycarboxylate superplasticizers could allow to create concrete structures with strength and density compared with traditional concrete materials. The ongoing progress in research will provide efficient and economically reasonable solutions.

The reuse of bigger fractions, mainly in geotechnical engineering, may successfully substitute natural granular materials. However, the imposed energy, related to most popular compaction methods, may have harmful effects in neighbouring structures by means of dynamic impact of ground transmitted shocks and vibrations. Currently, numerous researchers try to summarise experiences for the recommendations concerning different technologies and kind of surrounding structures. Some examples were juxtaposed in works of Brzakala [20] and Herbut [21, 22]. The last author also proposed an original method of reducing these negative impacts by means of active generator [23].

Bigger requirements are posed in marine engineering. Some case studies which highlight the successful use of marine mattresses were presented by Fiske [8], highlighting the environmentally sensitive erosion control system at Boston Logan International Airport; series of breakwaters in an estuary off the coast of Hilton Head, South Carolina; bridge scour protection system at the Kennedy Space Center in Cape Canaveral; and presented above system of marine mattress filled with recycled concrete aggregates for a shoreline protection system at the New Orleans, Louisiana Landbridge project. The technology is however environmental friendly at construction phase. Simple filling of gabions or mattresses doesn't really impose any environmental costs like heavy noise or vibrations.

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