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Experimental investigation of different fill materials in arch bridges with particular focus on Pearl-Chain Bridges

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HIGHLIGHTS

- The strength and durability of three fills for arch bridges were tested and compared.
- Sub-base gravel, cement-stabilized gravel and pervious concrete were investigated.
- Advantages and disadvantages for the three fill materials are listed.
- Recommendations for fill in Pearl-Chain Bridges are given.

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ABSTRACT

Pearl-Chain Bridge technology is a recently developed prefabricated arch solution for road and railway bridges allowing faster, more environmentally friendly, and cheaper bridge construction. This study compared the strength and durability properties of three different types of fill material to find the most optimal fill for Pearl-Chain Bridges. Sub-base gravel, cement-stabilized gravel, and pervious concrete were tested with respect to compressive strength, stiffness, splitting tensile strength, permeability, freeze–thaw durability, and shrinkage. This paper summarizes the advantages and disadvantages of implementing the different types of fill material in arch bridges, particularly in Pearl-Chain Bridges.

1. Introduction

The fill material resting on the arch in closed-spandrel arch bridges is an important part of the construction with respect to the bridge's structural system and the durability. Bridges are designed for a service lifetime of a minimum of 100 years, whereas all other constructions are designed for only 50 years [1]. This length of time places certain requirements on the materials used in bridges, including the fill material. A typical closed-spandrel arch bridge consists of the arch structure itself (made of concrete or masonry), spandrel walls, and a fill material, as shown in Fig. 1.

The static system of an arch bridge is based on the arch being in constant compression, first of all because of the considerable dead load from the fill material. Even when the arch is exposed to tensile stresses, such as from traffic loads, the compression force in the arch arising from the dead load of the fill is so large that the resulting force is most often also a compression force. Thus, reinforcement is rarely found in old masonry arches, such as the ancient Roman viaducts, and many of these arch constructions still exist 2000 years after they were constructed, which bears witness of the superiority of this type of construction. However, the fill material in arch bridges is more than dead load ensuring stabilization of the arch; it also supports the road surface and in arch constructions with a large rise/span ratio, the fill contributes to the load carrying capacity of the arch structure through soil-structure interaction in which the passive soil pressure on the arch structure helps resist the horizontal forces from the load [2]. Until now, fill has only transferred vertical traffic loads from the road surface to the arch, and does so for the present Pearl-Chain Bridge research project described in Section 1.2.4; however, during the project the inventor of Pearl-Chain structures, Kristian Hertz, discovered a possibility of increasing the load-bearing capacity of the arch bridge by incorporating the fill as a structural part of a new design, which he calls a "sandwich arch bridge" (see Section 1.2.4).

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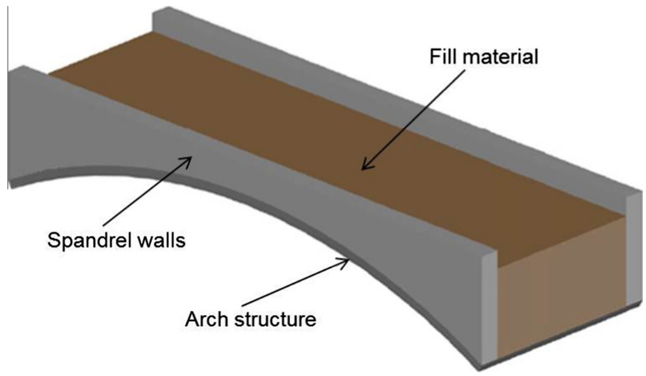

Fig. 1. Typical closed-spandrel arch bridge construction with arch structure, fill material, and spandrel walls to retain the fill.

Throughout history, various types of fill have been used worldwide, depending on several factors, such as economic considerations and the static system of the arch bridge. Typical types of fill can be divided into two categories:

- Granular (unbound) materials including soil [3–5].
- Cementitious (bound) materials [6,7].

The fill material itself is a vulnerable part of the construction. Fill made from poor quality material or with a lack of compaction is sensitive to deterioration and defects [3]. Water trapped in the fill because of bad drainage or poor permeability can cause problems during winter when the bridge is exposed to freezing from below, above, and from the sides. Negative temperatures of the surrounding air create a freezing front that moves through the fill, and if the fill material is granular and water is trapped in it, ice crystals form and coalesce into ice lenses that can cause frost heaving. The expansion of the fill due to frost heaving will damage the construction by either exerting a high pressure on the spandrel walls or by cracking and deteriorating the road surface. Moreover, water trapped in granular fill reduces the strength of the fill material, which also results in the bridge's overall deterioration. Several examples show how old arch bridges have been strengthened by replacing old granular fill with concrete fill [3]. However, cementitious fill materials are also sensitive to frost exposure. Freezing and thawing can cause internal damages as well as scaling if the pore structure of cementitious materials is not properly designed; therefore, concrete used as fill material must be designed carefully to avoid this result.

1.1. Fill used in Danish in situ arch bridges

To create an overview of the fill material used in previous bridges, we reviewed the accessible drawings of Danish closed spandrel arch bridges. Among the approximately 11300 Danish bridges registered as road- or railway-carrying, less than 5% are closed-spandrel arch bridges. The number comprises all bridges owned by the Danish Road Directorate and the Danish railway traffic, but only 70% of the Danish municipal bridges, since these latter are not sufficiently registered. However, since most arch bridges are older, the amount of technical drawings is limited. For all bridges with accessible technical documentation, a well-grained, often coarse grained, gravel material was prescribed to be filled around the arch. In some cases this well-draining gravel material was only prescribed for the fill in the vicinity of 30 cm of the arch, and the remaining fill was either a well-compacted sand fill or a cement-stabilized gravel fill. We did not see any examples of concrete fill.

1.2. Fill used in prefabricated arch bridge systems

The arch is rarely chosen for in situ bridges nowadays because of the extensive scaffolding usually required to construct arch bridges. This requirement involves comprehensive preparatory work, intensive labor, and road closure for weeks because the scaffold and formwork take up a lot of space. Because it is no longer economically beneficial to cast in situ arch bridges, a number of different prefabricated arch bridge systems have been developed. However, currently none of these prefabricated arch systems have gained ground in Denmark. We will now review three examples of well-established prefabricated arch bridge systems that are all so-called closed-spandrel arch bridges that work on the principle of soil-structure interaction. Finally, we will present the newly developed Danish Pearl-Chain Bridge technology that can be constructed without application of expensive curved molds and erected quickly without unnecessarily disturbing traffic.

1.2.1. The FlexiArch bridge system

The Macrete FlexiArch bridge system was developed in Ireland, and currently more than 40 FlexiArch bridges have been constructed. The arch structure is made of unreinforced precast concrete voussoirs connected by a flexible polymeric geotextile bonded to the top of all elements. The arch is flat on the ground, but shapes when it is lifted [1]. Two different types of fill have been tested on the FlexiArch bridges: a low-strength concrete backfill and a granular backfill. When using granular backfill, the gradation of the gravel was found to have a large influence on the load capacity. A well-graded fill resulted in lower deflections and higher load capacity than fill that was not well-graded. Developers of the FlexiArch system have not specifically defined a "well-graded fill"; however, they have found that the strength of FlexiArch bridges was much higher when using concrete backfill rather than granular backfill. Moreover, economical reasons urge the use of concrete backfill rather than granular because concrete needs no compaction, inhibits the ingress of flood water, and also allows the bridge to be used for traffic just a few days after installation [7].

1.2.2. The TechSpan bridge system

The TechSpan bridge system was developed in the United States, and currently more than 500 TechSpan bridges have been constructed. The superstructure is made of two-piece, funicular curve-shaped, precast arches that are lifted into place using a crane. The total width of the bridge depends on the number of arches placed next to each other. The arch is filled with a granular material. The fill material around the arch is divided into three zones. Zone 1 is select granular material placed 1.0 m around the perimeter of the arch structure. Compaction of the material in zone 1 may be achieved through a light walk. Zone 2 fill material is placed vertically and horizontally around zone 1. Compaction of the material in zone 2 may be achieved with heavy compaction equipment without any vibration. Zone 3 is all remaining fill around the arch, with compaction achieved with heavy compaction equipment with vibration [4]. The type of fill used in zone 2 and 3 is not prescribed.

1.2.3. The BEBO arch system

The BEBO arch system was developed in Switzerland, and currently more than 800 BEBO arch bridges have been constructed. The arch construction is similar to that of the TechSpan arch. For smaller spans a single concrete element is used, but larger spans require two elements per arch. The description of the fill requirements for the BEBO arch system are more detailed compared with the FlexiArch and TechSpan systems. The fill is an integrated load-carrying part of the bridge structure, and therefore, must permanently fulfill that purpose. The filling operation creates one of the