Design Considerations and Innovative Approach for Restoration of Historic Landmarks in Old Montreal

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Abstract : Restoration of some streets in Old Montreal is achieved using granite pavers bonded with a mortar bed to a concrete slab. The technique was originally used for the pavement of St-Paul Street with stone bricks back in the 1800's. A similar approach is being used in 2016 to renovate the very same street, except for the materials used in casting the foundation slab. In order to space out the expansion joints and prevent drying shrinkage cracking, fibre reinforcement and an expansive component are incorporated in the concrete. The concept was successfully used in bridge deck rehabilitation projects such as Girouard Overpass deck overlay. The basic principle of this approach is to generate a chemical expansion in the concrete (200 to 300 $\mu\text{m/m}$) using an expansive component, and to restrain the generated expansion through the combined action of ordinary peripheral steel reinforcement in the slab and steel fibre reinforcement in the concrete. The objective is to mitigate shrinkage stresses by keeping the strain balance as low as possible and allowing the concrete additional time to develop sufficient tensile strength, such that the stresses induced in the concrete slabs will remain lower than the concrete tensile strength. Restraint of expansion by the steel fibres and the peripheral reinforcement induces an initial compressive stress in the concrete slab. A part of this stress is used to compensate for the drying shrinkage, whereas the remaining part (if any) is used to resist incidental restrained deformation (e.g. thermal strains) cracking. Concrete mixture proportioning, placement, and curing need to be optimized in order to achieve enough expansion to adequately control cracking due to restrained shrinkage. After proper moist curing of the slab, the pavers are bonded to its top surface using a latex-modified mortar (latex to cement ratio of about 11% by mass). The latex-modified mortar used as a levelling bed underneath the pavers has a low vapour permeability that partially seals the concrete surface and further contributes to minimize drying shrinkage cracking. Since 2011, various historic landmarks in the City of Montreal have been restored using concrete containing an expansive component. To this date, monitoring and performance reports have showed that the chemical prestress approach is quite effective in decreasing shrinkage cracking in paved street foundations, thereby allowing the placement of longer slabs with significantly fewer expansion joints.

1 INTRODUCTION

The Old Montreal district is classified by the Ministry of Culture and Communication of Quebec as a historical area, in which all streets should be covered with granite pavers.

The restoration of these historical streets is currently achieved with a new approach based on the use of chemically prestressed concrete slabs. The method consists in casting the street foundation slab with shrinkage-compensating concrete and restrain the expansion through peripheral reinforcement and the incorporation

of 40 kg/m^3 of steel fibres. In addition, the foundation slab is anchored to the granite curb-stones which are, in turn, anchored to the concrete slabs of the sidewalks (Figs. 1 and 2).

In order to ensure proper functioning of the whole system, the expansion joints of the foundation slab must coincide with those of the curb-stones and sidewalks (Fig. 1, 2).

2 TECHNOLOGICAL CHALLENGES

The major challenges faced in implementing this approach were intimately tied: first, to successfully cast es-

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essentially crack-free foundation concrete slabs and, secondly, to minimise the number of expansion joints.

Figure 1. Schematic of paved street foundation using the approach of the chemically prestressed concrete slab.

Figure 2. Peripheral slab reinforcement (4-20M rebars).

2.1 Cracking

When designing the street foundation slab in Nordic countries and assessing the risk for cracking, not only should drying shrinkage, thermal deformations and loading be addressed, but also the movements due to soil heaving. This phenomenon can cause significant reflective cracking in the pavement, as observed in a rehabilitated street in Montreal, where longitudinal cracks have appeared on the top surface of the pavement approximately five years after construction. Given that reinforcing bars are usually placed within the lower section of the slab, they are ineffective against the up-lifting force due to soil heaving. To overcome this problem, the use of steel fibre-reinforced concrete has been found successful, owing to its three-dimensional reinforcing action. In this respect, structural synthetic fibres might be used as an alternative to steel fibres, depending on various considerations, such as slab dimensions, loads, expected service life of the structure, casting and service exposure conditions, etc.

2.2 Joints

It is well known that joints in concrete slabs are weak spots that require frequent maintenance. Therefore,

foundation concrete slabs in restored streets should be cast with as little expansion joints as possible. As an additional requirement, for concrete slabs covered with pavers, the expansion joints must extend upwards and match with the paver jointing (Fig. 3). This situation requires a special attention to match the paver's joints with the slab expansion joints. Omitting this design consideration will block and deactivate the expansion joints of the slab foundation.

Another issue that should be taken into consideration is the restraint of the adjacent zone of pavers in both sides of the expansion joint. Since the latter is usually filled with compressible materials, it allows for a horizontal displacement of adjacent pavers. As a consequence the abutment between the first rows of pavers located to the right and left of the joint is weakened. Failing to fix and strengthen this zone decreases the resistance of pavers facing traffic and breaking forces of vehicles. This problem can be treated by securing the last three rows of pavers (or one foot width on each side of the expansion joint) with an epoxy-based mortar that provides strong adhesion (Fig. 3).

Figure 3. Installation of the expansion joint and the adjacent pavers.

3 APPROACH OF CHEMICALLY PRESTRESSED CONCRETE SLAB

The first time this approach has been applied in Montreal was for the restoration of Place d'Armes in 2011. In this project, the usual 32-MPa air-entrained concrete ($w/b \leq 0.45$) was prepared with an expansive component and was moist cured for 7 days.

The approach is essentially based upon the generation of a chemical prestress in the concrete using an expansive component (free expansion of the order 200 to 300 $\mu\text{m/m}$). The induced compressive stress is intended to counteract the tensile stresses induced later by restrained shrinkage and thus prevent cracking. In order to be effectively, the slab expansion needs to be adequately

restrained, which is achieved in the present case through peripheral reinforcement and incorporation of steel fibers (40 kg/m³) in the concrete mixture.

The main objective of generating early expansion in the concrete slab is to mitigate shrinkage stresses by reducing the net strain balance and, at the same time, allowing the concrete additional time to develop sufficient tensile strength, such that the stresses induced in the concrete will not exceed its tensile strength. The process is illustrated in Fig. 4. Restraint of expansion by the steel fibers and the peripheral reinforcement causes a compressive stress to develop in the concrete. A part of this stress is used to compensate for the drying shrinkage, whereas the remaining part (if any) is used to resist incidental restrained deformations (e.g. thermal strains).

Figure 4. Schematic comparison of deformations in ordinary concrete and concrete containing an expansive component.

3.1 Where does this approach come from?

The technique of chemically prestressing concrete slabs has been inspired from an overlaying repair method implemented at the City of Montreal, notably in the rehabilitation of the Girouard overpass deck (Fig. 5). In the latter project, air-entrained fibre-reinforced-concrete overlays containing either a shrinkage reducing admixture (SRA) or an expansive component were used (R. Gagné et al. 2008).

4 APPLICATION (ST-PAUL STREET)

Over the last seven years, a number of street rehabilitation projects were executed in the City of Montreal using the chemical prestress technique: the Place d'Armes (2011), Bonsecours Street, St- Gabriel, Bonneau Street (2015) and, more recently, St-Paul Street (2016) projects. Monitoring of these projects has showed the effectiveness of the technique. The restoration of St-Paul

Street in Old Montreal represents a good example of the benefits of rebuilding the concrete slab foundation with steel fiber reinforced concrete containing an expansive component.

Figure 5. Schematic illustration of the concrete slab chemical prestress generated with an expansive compound.

An overall length of 1.3 km of the commercial and touristic street were planned to be restored in three phases; the first one was completed in 2016 and the two others are in progress. The first segment is 256 m in length, with an average width of 5.5 m and was executed in seven sections, separated by expansion joints (Fig. 6). The latter, which also act as construction joints, were reduced to a minimum in the design and located so that traffic disturbance would be minor. The length of the slabs varied based upon the aforementioned criteria (traffic and exploitation). The maximum slab length was 44 m.

Figure 6. First phase of the St-Paul Street restoration, achieved in 7 sections over a total length of 256 m.

4.1 Concrete Mixture

Mixture proportioning, placement, and curing of concrete made with an expansive component have to be optimized in order to achieve enough expansion and provide effective restrained shrinkage cracking control (Table 1).

A *type G* expansive component (lime-based system per ACI 223 classification), was used to generate the required expansion. From previous projects, a dosage of

6% by weight of cement has been found adequate for this type of application.

Table 1. Mixture design of the concrete slab foundation.

Characteristics	Steel Fibers	Expansive Component	Comp. Strength (28 d)	Air Content
CSA Type 10 cement + SF*	40 kg/m ³	6 % (cement weight)	32 MPa	5-8
W/C=0.45				

* SF: silica fume

4.2 Fibers

The role of steel fiber reinforcement (40 kg/m³) was to act in combination with the peripheral reinforcing bars in “absorbing” and “storing” the expansion induced by the expansive component, to better protect the concrete slab against the detrimental restrained shrinkage effects. Another positive outcome of using steel fibers as an alternative reinforcement mean is the ease of concrete placement. With much less conventional reinforcing bars (only along the periphery of the form), the concrete ready-mix truck can circulate on the granular foundation and, as a consequence, concrete could be discharged with the chute, eliminating the need to use a pump (Fig. 7).

Figure 7. Concrete poured with the discharge chute, with no need for pumping.

4.3 Curing

In most concrete construction, curing is a very important operation. In fact, it is critical for concrete containing an expansive component, the required curing duration depending on the type of component being used. The street foundation slab that has been cast with concrete containing an expansive component was water-cured continuously for seven days. Such a curing regimen guarantees

the activation and consumption of the expansive component in the early hydration/hardening stages (Fig. 8).

Figure 8. Water-curing performed on the freshly cast concrete slab.

4.4 Pavers

After completion of the curing period, the granite pavers were bonded to the concrete slab using a latex-modified mortar. Particular attention has been paid to ensure a *saturated-surface-dry* condition (SSD) prior to the laying the mortar and pavers.

Granite pavers 150 mm thick, 120 mm wide and either 200, 240 or 280 mm long were used. Each size came with a specific shade and the three types were installed in a random fashion.

The arrangement has resulted in a pleasant architectural view for the street (Fig. 9).

Figure 9. General view of the St-Paul Street segment completed in 2016.

4.5 Mortar

The mortar was prepared using specific proportions of cement mixed with latex having a 23% solid material content. The three different latex-to-cement ratios were used to produce the following types of mortar mixture: *bonding* mortar (grout), *bedding* (levelling) mortar and *joint-filling* mortar.

4.5.1 Bonding Mortar (grout)

In each batch prepared for this type of mortar, 4 litres of latex were mixed with a 22.5-kg bag of cement. Immediately prior to installation, the pavers were immersed in this grout (third of the height) in order to enhance their bonding performance.

4.5.2 Bedding/leveling mortar

The levelling bed mortar was produced with a ratio of 3 litres of latex to 22.5 kg of cement. With its low vapour permeability, this mortar partially seals the concrete slab surface underneath and consequently minimizes its drying shrinkage cracking. Prior to placing of the levelling mortar, the concrete slab surface was brushed with the aforementioned *bonding* grout for optimum bonding performance.

4.5.3 Joint-filling mortar

Joint-filling mortar was produced with a proportion of 3.5 litres of latex to 22.5 kg of cement. This mortar was used to fill the joints (15 to 25 mm openings) between pavers.

5 PERFORMANCE FOLLOW-UP

As mentioned earlier, the pavement restoration technique presented herein is inspired from the chemical prestress approach previously implemented in the rehabilitation of the bridge decks with bonded concrete overlays. In one of the rehabilitation projects involving this approach (Girouard Overpass), the overlaid concrete slab has deliberately been left exposed to weather (no asphalt or granite paver cover) in order to monitor its long-term performance. A regular monitoring is being performed since the repair works. According to the most recent inspection (May 2018), no visible cracking that can be attributed to shrinkage could be observed after more than 12 years in service. A structural crack was found in the negative moment zone of the slab, but it does not represent a threat to the structural capacity and safety.

Concerning more specifically the pavement rehabilitation projects at the City of Montreal in which the chemical prestress approach was exploited, the observed performance so far, notably in the case of the St-Paul Street project, is overall quite satisfying. No indication of deterioration or cracking could be found on the surface of restored streets, and no remedial work is required to date.

6 CONCLUSION

An innovative approach using a judicious materials combination for the restoration of historical paved streets has been presented. The results of the technique are evaluated 7 years after it was first implemented. Based on the results yielded in the different projects where it was used, the following conclusions can be drawn:

- the chemical prestress approach is robust and durable under extreme weather conditions (Nordic climate conditions);
- it permits the casting of longer foundation concrete slabs, with fewer expansion joints;
- it can minimize or even eliminate the cracking risk, and therefore increase the service life of restored streets;
- from a practical point of view, it is recommended to replace conventional reinforcing bars by fibers reinforcement, as it effectively addresses the cracking risk associated with shrinkage and soil-heaving;
- with its low vapor permeability, latex-modified mortar used as a bedding material on top of a foundation slab can be considered as an effective vapor barrier that contribute to reduce / prevent shrinkage cracking in the latter;
- the use of the latex-modified mortar for joint-filling is effective in terms of its resistance to weathering, freeze-thaw cycles, scaling, and traffic loading.

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