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Behaviour and Performance of Concrete Sidewalks

by Balvant Rajani

Sidewalks are key elements of urban infrastructure, have a high replacement cost and often fail prematurely. This Update reviews current construction practices and the types of deformation and damage that reduce service life.

Sidewalks allow pedestrians to walk safely and comfortably in a well-defined space. Of the roughly 100,000 kilometres of sidewalks in Canada, it is estimated that 15 to 20% are in need of replacement at a cost of $1.5 to $2.4 billion. The average service life is 20 to 40 years and is dependent on the geographic location and the quality of construction. In some western Canadian cities, premature failure is common one to five years after construction.

Figure 1. Flexible sidewalk under construction.

Figure 2. Concrete slab-on-grade sidewalk under construction.

In North America, there are two broad categories of sidewalks – flexible and rigid. Asphalt and interlocking brick sidewalks are flexible (Figure 1). However, the vast majority of sidewalks in North America are the rigid concrete slab-on-grade type (Figure 2). This Update therefore focuses on performance issues of concrete sidewalks with emphasis on why they fail. Another Update reviews best practices for prolonging sidewalk life.[1]

Concrete sidewalks are economical to construct and when built well, are long-lasting and attractive. They are typically slabs-on-grade with widths from 1.2 to 2.0 m, slab lengths usually slightly greater than the width, and a thickness of 100 to 150 mm.

Older designs consist of a flat concrete slab of uniform thickness adjacent to an L-shaped beam that forms the curb and gutter, usually with a full-depth joint separating the two components. More recent sidewalks are a monolithic design without full-depth joints between the flat slab, curb, and gutter. The monolithic design is fast to construct and eases vehicle access into driveways. The two designs provide comparable performance.

In new subdivisions, sidewalks are often constructed by concrete extrusion whereby the grading of the native soil, compaction, and placement of the concrete are done in a single pass.

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Attributes of Good Sidewalks

The four important attributes of sidewalks are:

- **Safety:** Uneven walking surfaces resulting from differential settlement are potential trip points for pedestrians. A study of injuries from pedestrian falls conducted in Victoria, BC found that cracked and uneven sidewalks caused 40% of all injuries from falls.[2]
- **Walking comfort:** Comfort usually receives much less attention than appearance and serviceability. [Japanese research found that flexible sidewalks such as asphalt offer better walking comfort compared to rigid sidewalks.[3]]
- **Appearance:** Different jurisdictions have different values when it comes to appearance. Whatever the type of sidewalk, damage adversely affects the appearance.
- **Serviceability:** Serviceability is the ability of a sidewalk to remain functional (that is, to be safe, provide good walking comfort and have a pleasing appearance) for a long period of time with a low cost of ownership.

Current Practice

Sidewalks are constructed over a wide variety of native soils across Canada. When the native soil has been well graded and uniformly compacted, it becomes the subgrade for the sidewalk. The sub-base is a layer, usually 100 to 150 mm deep, of compacted granular material placed between the subgrade and the concrete slab. While not always used, a sub-base is highly recommended because it reduces tensile stresses and consequent sidewalk cracking. It also provides a cushion for uniform support by bridging over minor subgrade defects. This is particularly important where the underlying subgrade soil is susceptible to shrinkage from moisture depletion and/or frost heave during cold seasons.

The concrete used for sidewalk construction in Canada typically has a compressive strength of 25 to 35 MPa. The mix proportions and properties are consistent with those used for other common concrete applications such as floor slabs. Steel reinforcement is not recommended because the reasons for using reinforcing in other types of slab-on-grade construction like floor slabs do not apply to sidewalks.[5] The reasons why reinforcing is not required are as follows:

Figure 3. Rigid body uplift (tilt).

- The appropriate location of control or cut joints in sidewalks is effective for controlling shrinkage-induced cracks.
- The width and the length between sidewalk control joints is small, generally, between 1.2 and 2.0 m, and therefore thermally induced stress is not the major concern and does not warrant reinforcing.
- Sidewalk slabs are not normally subjected to high loads and therefore reinforcing is not needed to provide moment capacity. However, sidewalks crossing driveway entrances will experience normal vehicle loads and occasional truck loads. It is preferable to use steel reinforcement mesh for these locations.

Modes of Deformation

An extensive study of sidewalk behaviour carried out by NRC's Institute for Research in Construction focused on the Prairie Provinces where soils and climate conditions are severe.[4] The findings of the study apply to a lesser extent to areas of Canada where conditions are less severe. Although large areas of both the Prairie Provinces and parts of eastern Canada are overlain by frost-susceptible soils, severe damage to sidewalks occurs more commonly in the Prairies. This is due to the cold climate and fluctuations in soil moisture. In addition, many parts of the Prairies have silty soils, which are particularly prone to frost heave.

There are four major deformation modes for concrete sidewalks:

1. Rigid body uplift or settlement is the tendency for a sidewalk slab to rise, subside or tilt as a result of expansive native soils, frost action, or thermal expansion of the concrete slab (even when a good granular sub-base is provided) (Figure 3).
2. Tensile-shrinkage is deformation resulting from tensile stresses (Figure 4a) caused by the shrinkage of underlying soils from

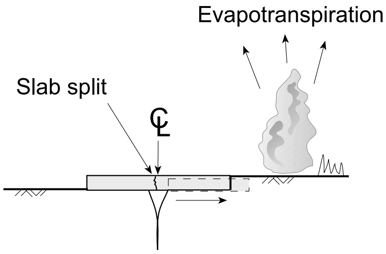

Figure 4a. *Tensile shrinkage.*

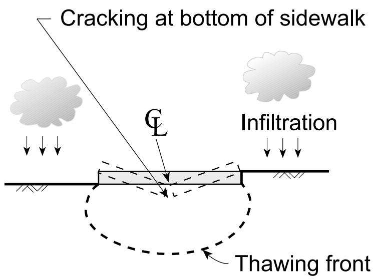

Figure 4b. *Sagging.*

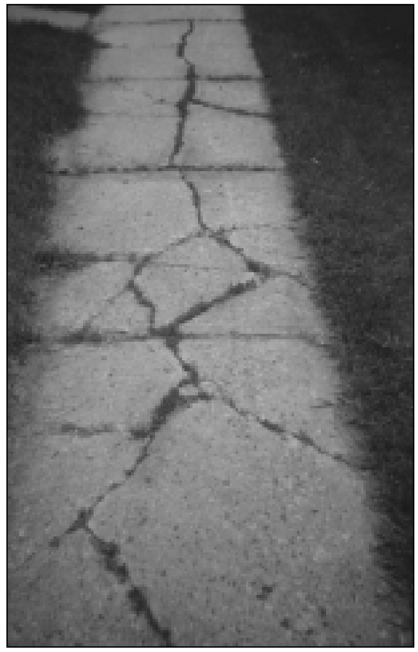

Figure 5. *Two or more deformation modes often occur simultaneously.*

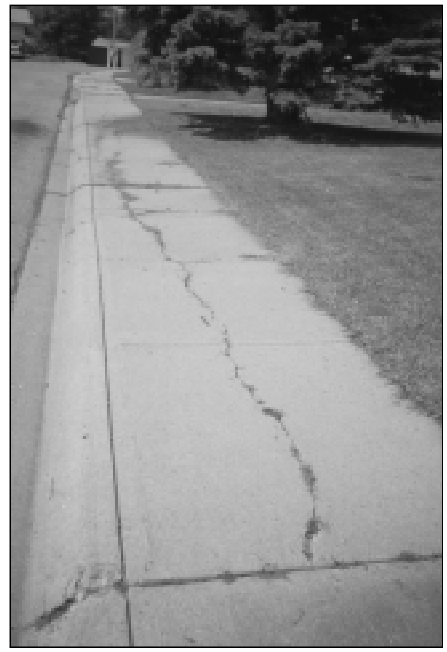

Figure 6. *Longitudinal cracks usually occur in the middle third of the sidewalk.*

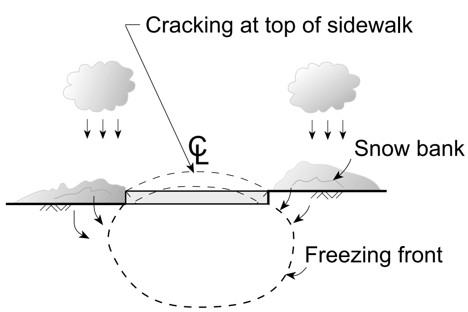

Figure 4c. *Hogging.*

decreasing moisture content. As a clay or silty subgrade dries, the strong bond of the subgrade to the underside of the concrete induces tensile stresses in the concrete slab as the subgrade shrinks. The concrete slab will crack when the tensile stress exceeds the tensile strength of the concrete.

3. Sagging is the unequal movement of the slab as a result of the centre of the sidewalk having a larger thaw settlement than at the edges, or native soil conditions where clays swell significantly at the edges. It leads to longitudinal cracking (Figure 4b).
4. Hogging is also unequal movement of the slab but it is caused by frost heave or upward vertical movement due to swelling of clay native soils being greater at the centre than at the edges. Like sagging, hogging leads to longitudinal cracking (Figure 4c).

It is rare to find one form of deformation in isolation. Often, two or more forms of deformation are evident (Figure 5). Deformation may or may not result in damage. Damage to sidewalks only occurs when tensile strains caused by one or more modes of deformation exceed the tensile failure strain of the concrete.

Types of Damage

Damage due to Poor Sub-Grade

Most concrete sidewalk cracks initially appear as hairline cracks. This means the forces acting on the concrete slab are inducing stresses that exceed the tensile strength of the concrete. Deformation of a concrete slab-on-grade may result in longitudinal cracking[6] (the most common type of sidewalk damage), transverse cracking and corner breaks.

Longitudinal cracks (Figure 6) occur primarily in the middle third of the sidewalk and are prevalent in the Prairie Provinces. These cracks can extend through several expansion joints before stopping abruptly. If the cracks do not open, and if no faulting develops along them, they do not pose a safety hazard. However, this type of crack normally opens up with time and it is common to observe faulting of 10 mm or more (Figure 7a).

Transverse cracks (Figure 7b) also result from non-uniform subgrade compaction rather than an overall lack of compaction. However, transverse and longitudinal cracks can also develop where sidewalks are subjected to high vehicle loads even when a granular sub-base has been provided. Both types of cracking are a major concern, especially if a significant tripping edge (faulting) develops.

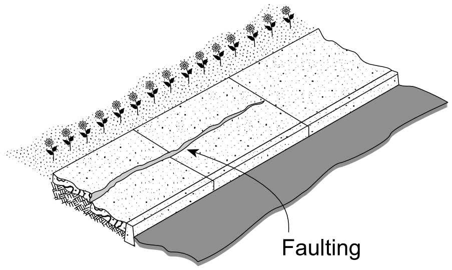

Figure 7a. Faulting is a change in elevation across a crack that can become a tripping hazard.

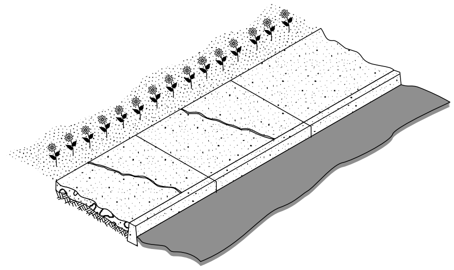

Figure 7b. Transverse cracks.

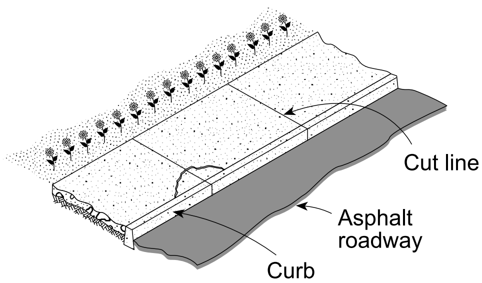

Figure 7c. Corner cracks ("D" crack).

Corner cracking or "D" cracking (Figure 7c) results primarily from non-uniform subgrade compaction rather than an overall lack of compaction effort. It occurs in many parts of Canada including areas where native soils are not particularly frost susceptible. The subgrade may also consist of soils that are susceptible to frost movement or movement from shrinkage (expansion and contraction) resulting from changes in moisture content. Like other forms of cracking, "D" cracking adversely affects the appearance and may become a tripping hazard if there is differential movement.

Cracking may or may not result in faulting (differential movement). If the slab returns to its original position after seasonal movement, damage may not occur, at least not initially. However, it is more likely that uplift or settlement will result in faulting between adjoining slabs, which poses a safety hazard. Uplift may also cause corner breakage as a result of friction at the control joint (cut line) when the slabs rise and subside.

Damage due to Concrete Problems

Concrete failure results from either a) poor concrete quality (for example, poor proportions, presence of deleterious materials such as iron-stone or shale, and low air entrainment) or b) poor placing and curing practices. Both lead to surface defects such as spalling, pop-outs and scaling. Such failures affect the appearance and may also become a safety concern depending on the degree of roughness on the walking surface.

Damage due to Trees

Trees planted near sidewalks are known to cause damage in two ways. First, during periods of extreme dry weather, the tree roots can accelerate moisture depletion in the subgrade, leading to the tensile-shrinkage mode of failure. The damage is aggravated when the sidewalk lies directly on clay that is prone to significant volume change on moisture depletion.

Second, certain types of trees have root systems that are more likely to remain closer to the surface where they can potentially uplift or tilt concrete slabs. This type of damage is a long-term threat that progresses slowly as the tree and root systems become larger.

Summary

Sidewalks are important features of the urban environment and are a large financial investment. Faulty construction results in deformation of the sidewalk that may result in damage that adversely affects the desired attributes of safety, walking comfort, appearance and service life.

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