Concrete Sidewalk Design Analysis and Optimization for Improved Life Cycle and Sustainability

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ABSTRACT

The City of Calgary (The City) has a multimillion-dollar sidewalk replacement backlog. The condition-based preventive maintenance and the corrective maintenance are faced with challenges with limited manpower to conduct condition assessments and funding for sidewalk maintenance.

A survey of the current sidewalk designs specified across major municipalities in Canada confirmed that the sidewalk structure in Calgary, including concrete thickness and the use of granular base materials, is one of the thinnest. The most common sidewalk damage/failure patterns in cold climates are well recognized, but the impact of the sidewalk design on the service life and the maintenance needs relies predominantly on limited inspections and reporting process for the asset. The structural assessment of different sidewalk designs was conducted using the finite element analysis (FEA). The model inputs were selected based on local climate and variations in concrete thickness, base material thickness, and soil conditions. A total of 36 models were analyzed for structural adequacy and the findings of the FEA formed the basis for the Best Construction Practices recommendations for concrete sidewalks in Calgary. The rationale behind the recommended changes to the sidewalk structure is discussed in conjunction with the need for a more stringent quality assurance and verification process. The life cycle cost analysis of selected designs is provided. The importance of data management to assess the effectiveness of the sidewalk repairs and to determine the rate of sidewalk deterioration is recognized.

BACKGROUND INFORMATION

The City of Calgary has a multimillion-dollar sidewalk replacement backlog and Tetra Tech Canada Inc. was retained to evaluate the causes of premature failure of concrete sidewalks and provide Best Practices for Concrete Sidewalk Construction. The purpose of the study was to determine the impact of changes from the current sidewalk design, as in the 2015 Calgary Roads Construction Standard Specifications, on the initial cost and the expected performance over the life cycle and to identify construction practices that will reduce the backlog rate of the sidewalk infrastructure owned by The City. An analysis of how updating the current policies, procedures, and specifications may help to alleviate the cost of replacing defective sidewalks, curbs, and gutters and extend the useful life of these assets was also conducted. A survey of the sidewalk designs in several municipalities was conducted and the summary is presented in Table 1.

Table 1. Municipal Survey Summary

Municipality	Concrete Thickness (mm)	Granular Base (mm)
Calgary	*100*	*Not required*
Edmonton	120	150
Lethbridge	130	100
Red Deer	115	Not required
Toronto	150	150
Hamilton	125	150
Kitchener	125	125
Guelph	125	75

Table 1. Municipal Survey Summary		
Municipality	**Concrete Thickness (mm)**	**Granular Base (mm)**
Windsor	115	50
Kingston	125	100
Regina	130	150
Winnipeg	100	Base course as required
Saskatoon	115	20 mm levelling course
Saint John	100 (150 at driveway)	150
Vernon	120	Min 100
Vancouver	100	100
NRC[1]	Min 100	150
Hartford, Connecticut	150	150
Wisconsin DOT	Min 100 (150 at driveway)	Min 100
Florida Tech	150	150

Note: [1] National Research Council (NRC) Construction Technology Update No. 54 Best Practices for Concrete Sidewalk Construction.

It is important to note that not only does The City have the thinnest sidewalk design specified, but also there is no requirement for granular base material under the concrete sidewalk. Only one other Alberta municipality, the City of Red Deer, does not specify the use of granular base for sidewalk construction, but in this case, the thickness of concrete is 115 mm as opposed to 100 mm in Calgary. In addition, The City has the highest percentage of sidewalk replacements. Based on the report by Rajani, B., and Zhan, C., Edmonton and Calgary had the highest mixed mode sidewalk damage. Since that time, Edmonton implemented the use of granular base for sidewalk construction and the longitudinal cracking caused by frost heave and overall sidewalk damage were reduced.

In 2008, a study was commissioned by The City to investigate specifications, inspections, and replacement review of the sidewalks, curbs, and gutters (Volk 2008) It was estimated that the replacement rate for concrete works in new subdivisions ranged from 30% to 35%. The two major causes for replacement identified in the report were settlements and third-party damages defined as damaged during the pre-Final Acceptance Certificate (FAC) phase. It was also identified that 70% to 80% of the settlements occur in the service connection trenches and that 55% of replaced sidewalks, curbs, and gutters were due to third-party damage. The report did not contain the damage/repair data after FAC when The City takes ownership of the concrete infrastructure.

The main causes of concrete deterioration after FAC continue to be random cracking due to subgrade saturation, settlement, frost heave, tree root damage, and poor construction practices.

FINITE ELEMENT ANALYSIS FOR STRUCTURAL ASSESSMENT

The structural adequacy of several sidewalk designs was assessed by FEA. The FEA is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. FEA subdivides a large problem into smaller, simpler parts called finite elements.

The properties affecting the structural performance of the sidewalk slab include the thickness of the slab, the thickness of the granular base, the degree of saturation of the subgrade soils, the concrete strength, and the vehicular loads.

The slab thicknesses and soil options are summarized in Table 2. Each option was analyzed in an unsaturated and saturated subgrade condition. An addition of synthetic macrofibre was considered for all options to a total of 36 models analyzed for structural performance.

Table 2. Sidewalk Slab Analysis Scenarios

Slab Thickness (mm)	Sub-Base Thickness (mm)	Subgrade Condition
100	0	Unsaturated
		Saturated
	100	Unsaturated
		Saturated
	150	Unsaturated
		Saturated
125	0	Unsaturated
		Saturated
	100	Unsaturated
		Saturated
	150	Unsaturated
		Saturated
150	0	Unsaturated
		Saturated
	100	Unsaturated
		Saturated
	150	Unsaturated
		Saturated

The Modulus of Subgrade Reaction for the subgrade soils and the soils with the granular base were assumed as follows (Table 3).

Table 3. Modulus of Subgrade Reaction (MPa/m)

Sub-Base Thickness (mm)	Condition of the Subgrade Soil		
	Unsaturated	Saturated	Frozen
0	28	14	100
100	34	17	100
150	38	20	100

Concrete properties used in the models were as CSA A23.1.1 for Class C-2 Exposure. The maximum bending stress for each slab-soil option is shown as a simple comparison of flexural strengths. It was assumed that the addition of fibre to the concrete mix would increase the flexural strength of concrete by 25%. In addition, four different Factors of Safety (FS) were considered with FS of >2 being code compliant.

The information about vehicular loads most commonly operating on the sidewalks was provided by The City and was utilized in the structural assessment of the sidewalk options.

The summary of the FEA for plain concrete is presented in Table 4 and for fibre reinforced concrete is presented in Table 5.

For plain concrete with a 28-day cylinder strength of 32 MPa, the nominal flexural strength, f_n = 3.39 MPa. Therefore, loading conditions resulting in loads higher than 3.39 MPa will cause cracking of concrete sidewalk when FS is assumed to be code less than 1. When higher FS are assumed, the critical loading is 2.26 MPa and 1.7 MPa for a FS of <1.5 and <2, respectively.

For fibre reinforced concrete with a 28-day cylinder strength of 32 MPa, the nominal flexural strength, f_n = 4.24 MPa. Therefore, loading conditions resulting in loads higher than 4.24 MPa will cause cracking of concrete sidewalk when FS is assumed to be code less than 1. When higher FS are assumed, the critical loading is 2.83 MPa and 2.12 MPa for a FS of <1.5 and <2, respectively.

Table 4. Maximum Flexural Stress, f_{max} (MPa), Compared to Strength, f_n , of Plain Concrete (f'_c = 32 MPa)

Slab (mm)	Base (mm)	Occasional Loads		Regular Loads							
		Moving Van		Toolcat	Bobcat		1 Ton Truck		Mower	
		Sat.	Unsat.	Frozen[1]	Sat.	Unsat.	Sat.	Unsat.	Sat.	Unsat.
100	0	5.90	5.20	3.81	4.07	3.60	3.42	3.10	2.00	1.80
	100	5.72	5.10	3.81	3.96	3.56	3.33	3.00	1.92	1.78
	150	5.57	5.03	3.81	3.85	3.44	3.20	2.90	1.88	1.75
125	0	4.24	3.72	2.68	2.85	2.58	2.40	2.21	1.39	1.25
	100	4.03	3.62	2.68	2.76	2.52	2.32	2.13	1.35	1.22
	150	3.95	3.55	2.68	2.72	2.44	2.26	2.07	1.31	1.21
150	0	3.25	2.83	2.06	2.21	1.98	1.83	1.65	1.05	0.95
	100	3.11	2.74	2.06	2.15	1.90	1.77	1.60	1.03	0.92
	150	3.00	2.67	2.06	2.07	1.87	1.72	1.56	1.00	0.90

[1] – Frost heave along centreline of sidewalk.

Legend	Factor of Safety, FS	Flexural Stresses	Condition of Sidewalk
	FS < 1	$f_{max} > f_n$ = 3.39 MPa	Cracked.
	1 ≤ FS < 1.5	3.39 MPa ≥ f_{max} > 2.26 MPa	Uncracked; high risk of cracking in event of small overload.
	1.5 ≤ FS < 2	2.26 MPa ≥ f_{max} > 1.70 MPa	Uncracked; medium risk of cracking in event of moderate overload.
	FS ≥ 2	$f_{max} \le f_n$ /2 = 1.70 MPa	Uncracked; low risk of cracking in event of substantial overload; code compliant.

Table 5. Maximum Flexural Stress, f_{max} (MPa), Compared to Strength, f_n, of Fiber-Reinforced Concrete (f'_c = 32 MPa)											
Slab (mm)	Base (mm)	Occasional Loads		Regular Loads							
		Moving Van		Toolcat	Bobcat		1 Ton Truck		Mower		
		Sat.	Unsat.	Frozen[1]	Sat.	Unsat.	Sat.	Unsat.	Sat.	Unsat.	
100	0	5.90	5.20	3.81	4.07	3.60	3.42	3.10	2.00	1.80	
	100	5.72	5.10	3.81	3.96	3.56	3.33	3.00	1.92	1.78	
	150	5.57	5.03	3.81	3.85	3.44	3.20	2.90	1.88	1.75	
125	0	4.24	3.72	2.68	2.85	2.58	2.40	2.21	1.39	1.25	
	100	4.03	3.62	2.68	2.76	2.52	2.32	2.13	1.35	1.22	
	150	3.95	3.55	2.68	2.72	2.44	2.26	2.07	1.31	1.21	
150	0	3.25	2.83	2.06	2.21	1.98	1.83	1.65	1.05	0.95	
	100	3.11	2.74	2.06	2.15	1.90	1.77	1.60	1.03	0.92	
	150	3.00	2.67	2.06	2.07	1.87	1.72	1.56	1.00	0.90	

[1] – Frost heave along centreline of sidewalk.

Legend	Factor of Safety, FS	Flexural Stresses	Condition of Sidewalk
	FS < 1	$f_{max} > f_n$ = 4.24 MPa	Cracked.
	1 ≤ FS < 1.5	4.24 MPa ≥ f_{max} > 2.83 MPa	Uncracked; high risk of cracking in event of small overload.
	1.5 ≤ FS < 2	2.83 MPa ≥ f_{max} > 2.12 MPa	Uncracked; medium risk of cracking in event of moderate overload.
	FS ≥ 2	$f_{max} \leq f_n/2$ = 2.12 MPa	Uncracked; low risk of cracking in event of substantial overload; code compliant.

The results of the FEA lead to the following conclusions:

1. The impact of the base gravel is relatively small for structural performance (up to 6% improvement) and should be considered for other than structural reasons, such as protection against frost heave longitudinal cracking.
2. The current specified sidewalk design thickness of 100 mm concrete has a predominantly high risk of cracking under the most common loads experienced on the sidewalks. This design fails under all types of loads and all ranges of safety factors.
3. The sidewalk thickness of 150 mm with a 150 mm thick gravel base provide the lowest risk of cracking for all assumed safety factors and the design is marked by black borders in Table 4.
4. When concrete sidewalk is reinforced with synthetic macrofibres, the sidewalk thickness may be reduced to 125 mm for a similar risk of cracking under the loads analyzed in the model. This design is marked by black borders in Table 5.

SIDEWALK DESIGN RECOMMENDATIONS

The current City Road Construction Specification for concrete type for sidewalks, curbs, and gutters is progressive when compared with other jurisdictions, and in line with the minimum CSA guidelines. The results of the FEA formed the basis for recommendations for Best Practices for Concrete Sidewalk Construction.

The proposed optimum sidewalk design is 125 mm of fibre reinforced concrete placed on 100 mm of granular base course. This is a significant change from the current specification of 100 mm concrete placed directly on subgrade soils. This design should prolong sidewalk life and advance the four key attributes: safety, comfort, appearance, and life cycle cost performance.

Sidewalk thickness is the single greatest factor in determining the structural capacity of ground supported slabs. Other factors include concrete strength and base support conditions.

The results of the FEA confirm that thicker sidewalks are not only able to withstand construction traffic if it cannot be controlled on site before the Construction Completion Certificate (CCC) phase, but also provide an improved resistance to cracking under frost heave and/or settlement and to damage from trees, snow clearing equipment, lawn care equipment, etc. Moreover, if edge grinding is necessary in the future due to slab displacement, the slab thickness will not be compromised below the structural capacity. The settlement of subgrade will cause less cracking of the thicker concrete allowing for the mud jacking option. Thicker concrete sidewalks would results in less damage and fewer replacements before FAC and extend the service life.

Fibres are specified in The City's specification in concrete in selected applications. Fibres are added to the concrete mix in plastic state and are effective in reducing plastic shrinkage cracking. They are also a viable alternative to conventional concrete reinforcement, as they are randomly distributed throughout the sidewalk cross-section instead of placing steel bars or wires in selected locations. The flexural strength of concrete is improved and the tendency to crack and the tendency for crack displacement under loads are reduced. Fibres are best suited for thin section shapes where correct placement of conventional reinforcement at mid-height in the slab is difficult, making it a good choice for sidewalks. The results of the FEA also confirmed that the addition of fibre to concrete mixes may reduce the optimum concrete thickness of 150 mm to 125 mm for a comparable risk of cracking under loads.

An inclusion of 100 mm granular base in the sidewalk design is a significant change to the sidewalk design in Calgary, which, with the exception of The City of Red Deer, is the only municipality in Canada without a granular base requirement for sidewalks. In the early 2000s, an extensive study of sidewalk behaviour was carried out by the NRC, Institute for Construction. Large parts of the Prairie provinces and parts of Eastern Canada are overlain by frost-susceptible soils but it is the cold climate and the fluctuations in soil moisture that are more common in the Prairies. In addition, many parts of the Prairies have silty soils, which are more prone to frost heave.

In collaboration with the cities of Winnipeg, Saskatoon, Regina, Edmonton, Calgary, and Camrose, NRC initiated a project to identify the underlying mechanisms that lead to longitudinal cracks in sidewalks. The study indicated that with comparable soils conditions, Calgary has the highest incidence of damage to sidewalks (30% to 60% replacements due to third-party damages, cracks, settlements, and gouges, Volk Consulting Report). The study did not consider the impact of the sidewalk design in Calgary and comparison with other cities, but it is likely no coincidence that the design specifications in Calgary are the thinnest of all jurisdictions and that Calgary is the only city that does not specify a granular base. Subsequently, NRC issued Construction Technology Update No. 54, titled Best Practices for Concrete

Sidewalk Construction (2002), stated the importance of proper preparation of the subgrade for optimum long-term performance. In 2004, another study was issued by The Federation of Canadian Municipalities and NRC titled Sidewalk Design, Construction, and Maintenance, A Best Practice by the National Guide to Sustainable Municipal Infrastructure. One of the recommendations of the study was a layer of 100 mm to 150 mm of compacted granular material because it reduces tensile cracking stresses and consequent cracking. The base material also provides a uniform support by bridging over minor subgrade defects. This is important when the underlying soil is susceptible to shrinkage from moisture depletion and frost heave during cold seasons. After the report was issued, the City of Edmonton specified placing 150 mm granular base under the sidewalks. Anecdotal evidence confirmed that since placing granular base under the sidewalks was mandated, the damage to sidewalks and the incidence of longitudinal cracking have been reduced.

The studies conducted by NRC, the data collected in the Prairies, and the final recommendations on the importance of granular base construction as a single preventive method for reducing detrimental effects of frost heave provide undeniable support for the changes to the design of sidewalks in Calgary.

While the contribution of the granular base to the structural performance of the sidewalk is small, it is significant for improvement of subgrade support in both saturated and unsaturated conditions.

It is not practical to remove unsuitable high frost heave susceptible soils under the sidewalks. Therefore, other measures should be considered. Granular base course under the sidewalk provides only limited thermal insulation but may act as a drainage layer to prevent subgrade saturation and frost heave and provides uniform support for concrete sidewalks. In addition, rigid insulation is beneficial for frost protection. This option also promotes uniform vertical movement and minimizes differential movement. The insulation can extend to the edges of the sidewalk to reduce effects of frost heave, and snow accumulated on the side provides additional insulation from the effects of freezing.

LIFE CYCLE COST ANALYSIS (LCCA)

In order to better understand the basis for LCCA, the definitions of a design life and a service life have to be clarified:

- **Design Life** – A period of time, specified by an Owner, during which a structure is intended to remain in service (time to block replacement).
- **Service Life** – Actual period of time during which a structure performs its design function without unforeseen costs for maintenance and repair (time to first flag replacement due to durability/structural failure).

The International Infrastructure Management Manual (IIMM) provides the following definitions:

- **Life** – A measure of the anticipated life of an asset or component.
- **Unplanned Maintenance** – Corrective work required in the short-term to restore an asset to working condition.

The Design Life is therefore comparable to “Life” from IIMM. There is no direct definition for the service life but the “Unplanned Maintenance” listed in IIMM is comparable to unforeseen costs for maintenance and repair for required service.

Based on the information from The City, the weighted average age of a sidewalk at the full block replacement is determined at 40 years.

The LCCA analysis presented below is based on the following assumptions:

1. Assumed design life of the sidewalk is 40 years.
2. Assumed service life of the current sidewalk design is 15 years.
3. The impact of steel reinforcement is not taken into consideration and macrofibre is used in the design, where applicable.
4. Assumed sidewalk failure due to concrete cracking – 30%.
5. Assumed sidewalk failure due to frost heave, settlement, and non-uniform compaction – 50%.
6. Assumed sidewalk failure due to winter construction (low temperature, frozen soil, and low compressive strength) – 80%.
7. Third-party damages before FAC are not considered but would be reduced with the more adequate sidewalk design.
8. The current costs of maintenance/replacement and preventative maintenance are not known and therefore are not considered but factored into assumed maintenance timing.

The summary of the service life predictions is presented in Table 6.

Table 6. Life Cycle Cost Analysis

Option	Design Life (Years)	Service Life (Years)	Construction Cost (% Increase from Option 1)	Miscellaneous Concrete Repairs(2)	Comments
100 mm concrete, no base gravel	40	15	X	5 to 10 years	
125 mm concrete with macrofibre and 150 mm base gravel	~50	35	X + 10%(1)	25 to 30 years	Macrofibre addition reduces shrinkage cracking potential and limits crack displacement. Gravel base reduces frost heave risk.
150 mm concrete with 150 mm base gravel	>50	45 (50 when fibre used in concrete)	X + 30%	30 to 35 years	Macrofibre addition reduces shrinkage cracking potential and limits crack displacement. Gravel base reduces frost heave risk.

Note 1. Fibre cost estimated at 5% premium.

Note 2. Preventive maintenance at 40% of assumed service life (equivalent of 25% to 30% drop in sidewalk quality) reduces rehabilitation costs.

The results of the analysis indicate that an increase in concrete thickness combined with the base gravel construction for limiting the effects of frost heave may significantly increase the service life of a sidewalk and defer the need (and reduce cost) of major rehabilitation. An addition of synthetic macrofibre further reduces concrete cracking potential due to shrinkage and prevents crack widening and displacement. Detailed analysis to determine the offset of the initial construction costs by the increased service life and reduced maintenance costs should be conducted when The City's costs of sidewalk rehabilitation and replacement are available.

The impact of the current design (unsustainable design) and the proposed options to the sidewalk structure (sustainable design) are presented on Figure 1. It illustrates how the structure design may influence the service life expectancy.

Service Life – Design 1 refers to the current sidewalk design, which requires corrective maintenance within 5 to 15 years to restore working condition. Service Life – Design 2 refers to the proposed changes in the sidewalk design to extend the time for intervention to over 30 years. At the end of the design life, the sidewalk is either decommissioned or undergoes a planned maintenance (major rehabilitation) or is replaced.

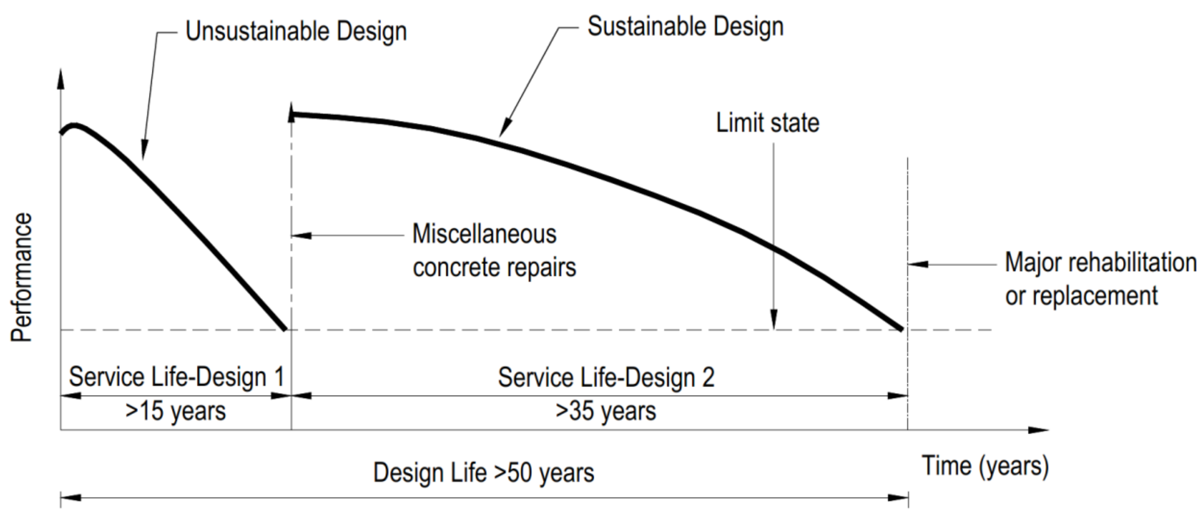

Figure 1. Schematic Representation of Performance of Infrastructure Systems

CONCLUSIONS

All the data available formed the basis for the optimum performance of the sidewalk design of 125 mm fibre reinforced concrete on a 100 mm of 25 mm gravel base. The rationale behind this design is summarized as follows:

- Sidewalk thickness is the single greatest factor in determining the structural capacity of ground supported slabs. The results of the FEA confirmed that a 150 mm thick slab is able to support most of the loads commonly experienced on the sidewalk, even for reduced safety factors.
- Synthetic fibre allows for a partial reduction of thickness to 125 mm but the cost of concrete, the impact of thickness reduction, and the cost of fibre needs to be evaluated. However, fibre provides additional advantages such as increased toughness, reduced plastic shrinkage, and control of crack displacement and is a viable alternative to wire mesh reinforcement.
- Granular base course improves the modulus of subgrade reaction of subgrade soils, provides a uniform support for concrete, and provides some protection against frost heave. NRC studies and experiences from other municipalities show enough evidence of improved sidewalk performance to be included in the sidewalk design. In addition, granular materials provide drainage and minimize the degree of saturation from surface infiltration.

- Rigid insulation should be considered in the areas where the soils are highly frost susceptible. The insulation also promotes uniform vertical movement and minimizes differential movement.
- The City's concrete sidewalk asset management program consists of a defect survey completed on an annual basis to ensure the concrete is maintained in a safe manner. Data collected from this survey is used to prioritize repairs and replacement upgrades through a variety of concrete programs. Root cause of damage/condition is not currently captured and this information would help in design, specification and construction of concrete sidewalks. Treating the root cause and not only the symptoms is important and would extend the service life of concrete sidewalks. In addition, there is a need to develop a rating for the sidewalk condition comparable to the roads asset management program.

REFERENCES

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