# Design of Waste Transfer Station Concrete Overlays against Premature Deterioration

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## FINAL REPORT

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# EXECUTIVE SUMMARY

To transfer solid waste to landfills, or other waste processing or disposal endpoints, waste collection vehicles deposit the collected waste at waste transfer stations (WTSs). In the majority of the WTSs, the waste is deposited on a concrete floor, from which waste handling equipment is used to transfer the waste to compaction equipment and/or large transfer vehicles. Premature deterioration of concrete floors in WTSs is often reported and is a major concern for the owners and operators of these facilities. Overlay replacement in these facilities has significant economic impacts including direct costs, operational delays, and planning hurdles. Unfortunately, published data on the contributing factors to the deterioration of concrete overlays in transfer stations and the mechanisms involved are virtually nonexistent.

The overall objectives of this research are therefore (i) to identify the contributing factors to the premature deterioration of concrete overlays in transfer stations, and (ii) to establish material design guidelines for the concrete overlay based on the observed degradation mechanism and operational conditions.

At the beginning of the project, the research team collected data through site visits and a survey. Results indicate that the service life of concrete floors in WTSs is significantly shorter than the service life expected by owners and operators; the findings support that the main factors are mechanical abrasion by waste handling equipment (e.g., loaders) as well as organic acid attack from waste leachate. Furthermore, a literature survey indicated that (i) simultaneous mechanical abrasion and organic acid attack has not been studied; (ii) existing abrasion resistance test methods are not suitable for investigating the simultaneous mechanical abrasion and organic acid attack mainly because of high variability of these test methods; therefore, there was a need to develop a new abrasion resistance test method for this project. Based on these findings, the research team (i) characterized the organic acid content of fresh leachate samples from the floors of WTSs and used the chemical concentration data to develop a synthetic leachate to simulate the conditions to which concrete is exposed at WTSs, (ii) developed a new abrasion resistance test method and supporting equipment, (iii) conducted abrasion resistance tests on cement paste and concrete in the presence and absence of exposure to leachate, and (iv) developed material design guidelines and recommendations for WTS floors.

The developed abrasion test method and equipment can be applied to cement paste, mortar and concrete materials with a maximum coefficient of variation of 4.4%, which is significantly lower than that of the existing abrasion test methods.

The results of abrasion tests on cement paste and concrete materials in the absence of exposure to synthetic leachate indicate that (i) the abrasion resistance of concrete is primarily controlled by the hardness and the volume fraction of the coarse aggregates, (ii) decreasing the water-to-

cement ratio (w/c) of a mixture may increase the abrasion resistance of concrete but its effect is, in general, smaller than the effects of coarse aggregate hardness and volume fraction, (iii) no general correlation exits between w/c and the abrasion resistance; and (iv) no correlation exists between compressive strength and abrasion resistance of concrete.

The results of abrasion tests on cement paste and concrete materials in the presence of exposure to synthetic leachate indicate that (i) the abrasion resistance of concrete is mainly a function of hardness of the coarse aggregates; (ii) w/c has a significant effect on the abrasion resistance of concrete exposed to organic acids, especially, when soft aggregates (limestone herein) that are reactive with organic acids are used; (iii) limestone coarse aggregates provide only a short-term buffer against organic acid attack and the abrasion resistance of high w/c concrete materials containing limestone aggregates decreases very rapidly in long-term exposure to organic acids; (iv) while the use of silica fume, polymeric fibers, and latex increases the abrasion resistance of concrete in the absence of exposure to leachate, their use decreases the abrasion resistance of concrete exposed to leachate.

These findings were used to develop guidelines and suggestions for the material design of WTS concrete floors including: (i) the use of a w/c lower than 0.36; (ii) the use of a minimum of 70% total aggregate by volume; (iii) the use granite coarse aggregates which do not react with organic acids; (iv) the avoidance of pozzolanic materials including fly ash, silica fume, slag, or other pozzolanic materials that reduce the amount of calcium hydroxide in concrete; and (v) the avoidance of polymeric fibers and latex modified mixtures.

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# 1

# Introduction

## 1.1. Introduction and motivation

The premature deterioration of concrete overlays in Waste Transfer Stations (WTSs) is a major concern for owners and operators of these facilities. Overlay replacement in these facilities has significant economic impacts including direct costs, operational delays, and planning hurdles. While overlay deterioration is mainly attributed to the mechanical abrasion caused by waste handling equipment, anecdotal evidence suggests that other factors might equally contribute to the overlay deterioration.

Unfortunately, published data on contributing factors to the deterioration of concrete overlays in WTSs and the mechanisms involved are virtually nonexistent. Contributing factors may include contact with acidic leachate from fresh waste, the type and operation of equipment used for handling waste, the amount of waste handled, and the lack of systematic structural design that accounts for concrete material deterioration. If the main contributing factors to deterioration are identified, then overlays can be designed to minimize deterioration, resulting in better long-term performance and predictability, and consequently, reduced life cycle cost for owners and operators.

The main objectives of this research are therefore (i) to identify the factors contributing to the premature deterioration of concrete overlays in WTSs, and (ii) to establish material design guidelines and recommendations for the concrete overlay based on the observed degradation mechanism and operational conditions.

## 1.2. Report Organization

At the beginning of the project, the research team collected data and information on the degradation of concrete floors through site visits and a survey that was distributed in collaboration with the Environmental Research and Education Foundation (EREF). The results of the site visits and the survey are presented in Chapter 2, Sections 2.1 and 2.2.

The results of the site visits and survey indicated that the main factors contributing to the degradation of concrete floors in WTSs were mechanical abrasion by waste handling equipment (e.g., loaders) as well as organic acid attack from fresh waste leachate. The literature review on the abrasion resistance of concrete is presented in Chapter 1, Section 1.4 and the literature review on acid attack resistance of concrete is presented in Section 1.5. The survey of the existing literature indicated that the simultaneous mechanical abrasion and exposure to fresh leachate has not been studied. Therefore, the research team developed a synthetic leachate based on the results of chemical characterization of 20 fresh waste leachate samples collected at WTSs. The analytical methods and results of the analyses, and the formulation of the synthetic leachate are presented in Chapter 2, Section 2.4. The methods used in for chemical analyses are presented in Chapter 5, Section 5.1.

The results of the literature review also indicate that the existing abrasion resistance test methods are not suitable for investigating the simultaneous mechanical abrasion and organic acid attack, mainly because of the high variability of these test methods. The literature review on the abrasion test methods is presented in Chapter 1, Section 1.3. The research team developed a new abrasion resistance test method and equipment for this project. Chapter 5 includes a description of the new abrasion test method and equipment. The new test method was used to study the abrasion resistance of cement paste and concrete in the absence and presence of exposure to leachate, and the results are described in Chapter 2, Sections 2.5 and 2.7, respectively. The findings from Chapter 2 were then used to develop material design guidelines and recommendations for WTS concrete floors which are presented in Chapter 3.

## 1.3. Literature review on abrasion test methods

For the purpose of this project, a proper abrasion test method was needed to mimic the actual conditions of WTS concrete floors subjected to friction force by vehicles. Multiple standard test methods for abrasion resistance testing of concrete are available in literature [5–18] as shown in Figure 1.1. Review of these test methods showed that none of them can realistically simulate concrete abrasion that occurs in WTSs, nor can they be used for quantifying the simultaneous effect of acid attack and abrasion since: (i) there are other abrasive forces, besides friction, involved in these test methods such as impact or carving by spikes (Figure 1.1b-f), (ii) samples

are submerged in media such as water (Figure 1.1f), and (iii) test conditions are not consistent with conditions in WTSs (Figure 1.1a and g). Therefore, a new test method was developed that can more realistically mimic the conditions in WTSs.

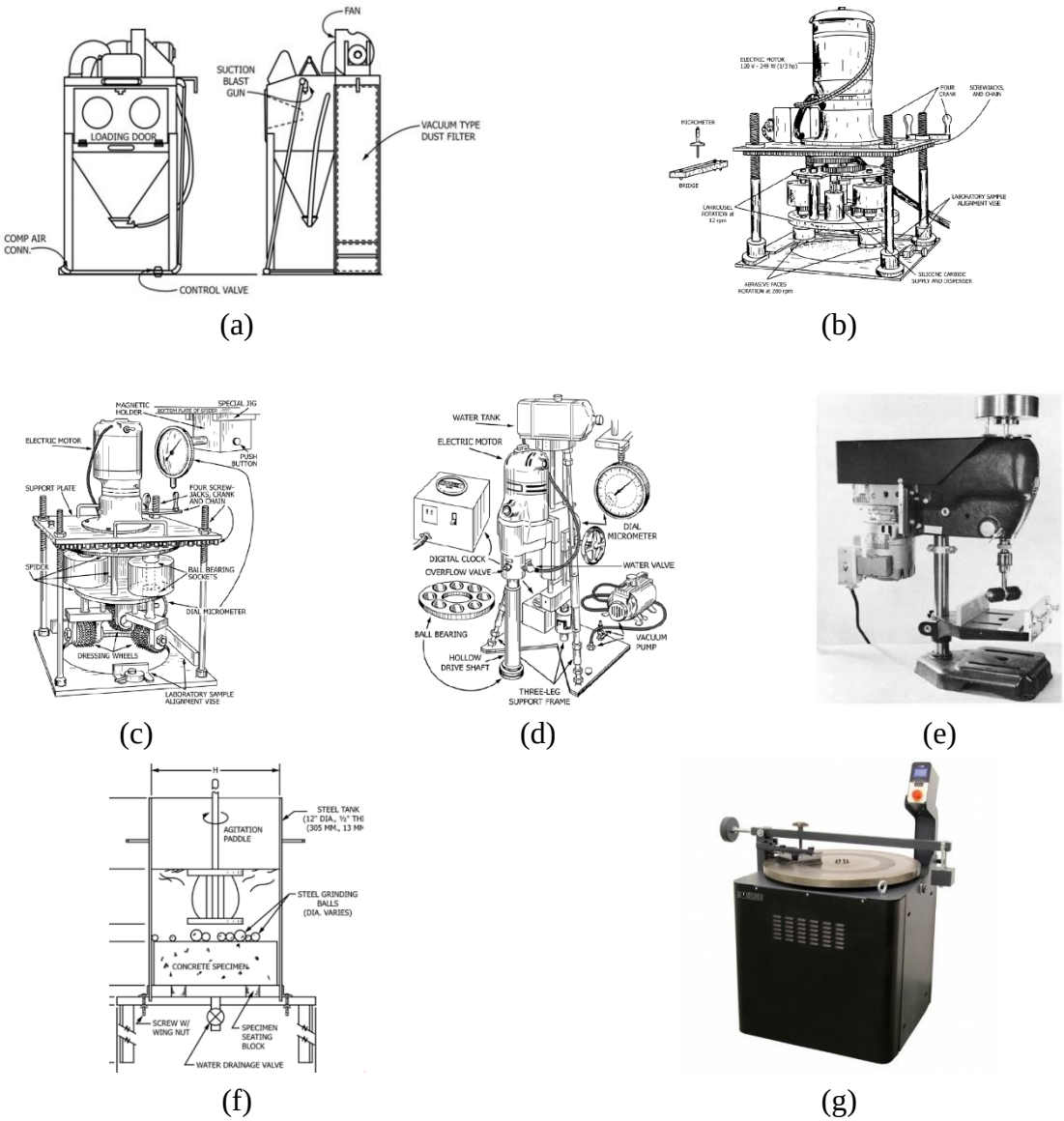



Figure 1.1: Existing abrasion test methods: (a) sand blast test (ASTM C418); (b) revolving disk (ASTM C779a); (c) dressing-wheel (ASTM C779b); (d) steel ball bearing (ASTM C779c); (e) rotating-cutter drill press (ASTM C944); (f) abrasion test under water (ASTM C1138M); (g) Bohme abrasion tester.

## 1.4. Literature review on the abrasion resistance of concrete

The abrasion resistance of concrete has been rather well studied and researchers have experimentally evaluated the influence of different factors on the abrasion resistance of concrete. For example, Table 1-1 summarizes some of the existing literature and highlights some of their findings. The literature cited in Table 1-1 indicates: (i) water-to-cement ratio (w/c) is a primary factor influencing abrasion resistance of concrete; (ii) coarse aggregates significantly influence the abrasion resistance of concrete; and (iii) there is an interest in relating the abrasion resistance of concrete to its compressive strength. With regards to the last point, in addition to the reported literature in Table 1-1, there have been significant efforts in correlating the abrasion resistance of concrete to its compressive strength; for example, multiple correlations between abrasion resistance and compressive strength has been reported including linear [7,9,23–28], quadratic [24], 2$^{nd}$ order polynomial [29,30], hyperbolic [31,32], exponential [33–36], and logarithmic [37]. Furthermore, other researchers have suggested that no correlation exists between abrasion resistance and compressive strength [8,11,16,38].

Table 1-1: Summary of selected previous research on the abrasion resistance of concrete.

| Publication | Year | Test method | Measurement | Highlights |
|---|---|---|---|---|
| Liu [39] | 1981 | ASTM C1138 | Mass loss | Decreasing w/c increases abrasion resistance and compressive strength. Abrasion resistance and coarse aggregate hardness are strongly correlated. |
| Sadegzadeh et al. [5] | 1987 | Developed[a] | Depth of wear | w/c ratio and finishing affect the abrasion resistance. Low w/c with repeated power finishing results in a high abrasion resistance. |
| Nanni [40] | 1989 | ASTM C779c[b] | Depth of wear | The ball bearing test method is only suitable for evaluating smooth surfaces and for small abrasion depths, providing coefficient of variation of about 15%; this test is not reliable when the surface has exposed coarse aggregates; both steel and synthetic fibers do not increase the abrasion resistance. |
| Langan et al. [38] | 1990 | ASTM C944 | Mass loss | The rotating cutter method has a large CoV, especially when the surface has exposed coarse aggregates; fly ash can increase both abrasion resistance and compressive strength; however, no correlation exists between them. |
| Laplante et al. [6] | 1991 | ASTM C779c[b] | Depth of wear | Silica fume slightly improves abrasion resistance; in low w/c concrete, type of coarse aggregate determines the abrasion resistance. |
| Dhir et al. [11] | 1991 | Developed[a] | Depth of wear | w/c has a significant influence on the abrasion resistance; moist curing improves abrasion resistance; silica fume does not increase abrasion resistance; water absorption test has more correlation with abrasion resistance than compressive strength. |
| Shaker et al. [41] | 1997 | ASTM C799[a] | Mass loss | Latex modified concrete (LMC) has a dense microstructure and a high abrasion resistance; w/c of the LMC was 0.26 and was compared to ordinary concrete with w/c = 0.42. |
| Limbachiya et al. [42] | 2000 | Developed[a] | Depth of wear | Recycled aggregate concrete has a similar abrasion resistance to normal aggregate concrete. |
| Siddique [12] | 2003 | IS 1237-1980[d] | Depth of wear | Abrasion resistance increases with fly ash content when used as fine aggregate replacement; abrasion resistance increases with compressive strength. |
| Li et al. [23] | 2006 | GB/T16925-1997[e] | Depth of wear | Nano $SiO_2$ and $TiO_2$ increase abrasion resistance more than polypropylene fibers; compressive strength and abrasion resistance are linearly correlated. |
| Yen et al. [13] | 2007 | ASTM C1138 | Depth of wear | 15% cement replacement with fly ash does not affect the abrasion resistance; abrasion resistance can be predicted using compressive strength, w/c, and fly ash content. |
| Kevern et al. [15] | 2009 | ASTM C944 | Mass loss | Concrete materials containing fly ash that are moist cured had the highest abrasion resistance and compressive strength. |
| Won et al. [43] | 2009 | ASTM C944 | Mass loss | Latex increases the abrasion resistance when the overall w/c ratio was kept same. |
| Nazari and Riahi [16] | 2011 | ASTM C1138 | Depth of wear | Abrasion resistance improves by replacing of Portland cement with $SiO_2$ and $Al_2O_3$ nanoparticles; abrasion resistance does not depend on compressive strength. |
| Rashad [7] | 2013 | ES: 269-2/2003[f] | Depth of wear | Replacing sand with metakaolin increases compressive strength and abrasion resistance; compressive strength is the most important factor influencing abrasion resistance. |
| Kabay [8] | 2014 | Bohme test | Mass loss | Basalt fibers increase flexural strength and abrasion resistance, but do not increase compressive strength; there is no correlation between compressive strength and abrasion resistance. |
| Rao et al. [9] | 2016 | ASTM C944 | Mass loss | Cement replacement with slag up to 50\% increases both abrasion resistance and compressive strength; compressive strength is the most important factor influencing abrasion resistance. |

[a] Abrasion tester was developed by the authors; [b] The ball-bearing test method; [c] The revolving-disk test method; [d] Indian Standard Specifications IS 1237-1980; [e] Ball bearing method according to Chinese standard:Q10; [f] Egyptian Standard Specifications [44]; [g] Testing method of concrete paving blocks; British and European standard BS EN 1338

The research team believes that the main motivations for developing a correlation between compressive strength and abrasion resistance of concrete include: (i) in general, concrete is specified by its compressive strength; (ii) measuring compressive strength is significantly easier and faster than the abrasion resistance measurements with existing ASTM test methods, and (iii) the existing ASTM test methods for measuring the abrasion resistance of concrete are difficult to perform, time consuming, and have high variability (see Table 1-2).

Table 1-2: Overview of abrasion resistance test methods.

| Test method | CoV[a](%) | Test duration (min) |
|---|---|---|
| Accelerated abrasion | 7 | 15 |
| ASTM C779a | 7 | 30-60 |
| ASTM C779c | 15 | 20 |
| ASTM C944 | 20 | Variable[b] |
| ASTM C1138 | 14 | 1440 |

[a] Coefficient of variation (%)
[b] Test continues until distinguishable depths of wears between specimens are obtained

## 1.5.Literature review on the acid attack resistance of concrete

The degradation of concrete exposed to organic acids is mainly attributed to the formation of water-soluble calcium salts resulting from the reaction of acids with calcium containing hydrated phases in cement paste [47]. For example, the following reaction between acetic acid and $Ca(OH)_2$ (CH) has been proposed [48]

$$2CH_3COOH + Ca(OH)_2 \rightarrow Ca(CH3COO)_2 + 2H_2O \quad (1)$$

The reaction (1) lowers the pH of concrete and subsequently results in the degradation of Calcium Silicate Hydrate (CSH). Since CH provides a buffer against acids and protects the CSH, concrete materials with a high cement content may provide a better performance in resisting organic acids [47]. On the other hand, the use of supplementary cementitious materials (SCMs) may reduce the resistance of concrete to organic acids due the conversion of CH to CSH by SCMs. Studies by in [49,50] suggest that high cement content is essential to increase acid attack resistance since higher cement paste volume contributes to increased neutralizing capacity. However, these studies have not considered simultaneous acid attack and mechanical abrasion.

High cement paste volume results in a lower abrasion resistance. Also, high cement paste content increases the volume instability and shrinkage cracking.

The reported results in literature concerning the effect of cement replacement with pozzolanic materials such as silica fume and fly ash are controversial. While it has been suggested in [51,52] that replacing cement with pozzolanic materials increase resistance to acid attack because of conversion of calcium hydroxide to C-S-H and consequent reduction of calcium hydroxide dissolution, results in [51] shows that mortars containing pozzolanic material show a lower resistance to acid attack especially at high concentration solution (i.e., 5%) as compared to Portland cement mortar. The reasons for these observations are not discussed in the literature.

The type and the chemical composition of the aggregates may also play a role in increasing the resistance of concrete against organic acids since aggregates such as limestone may react with acids and provide a buffer to protect the hydrated phases [53–57]. This may be caused by the contribution of limestone in maintaining an alkaline environment that protects the C-S-H.

While the degradation of concrete subjected to mechanical abrasion was studied (see Section 1.4) and factors affecting the degradation of concrete exposed to organic acids have been reported in the literature, to the best assessment of the authors, the degradation of concrete under the *simultaneous* mechanical abrasion and exposure to organic acids has not been studied.

# 2

# Results and Discussion

## 2.1. Site visits

The research team visited five WTSs in North Carolina (Pitt County transfer station in Greenville, Waste Industries transfer station in Fayetteville, Harnett County transfer station in Dunn, Waste Industries transfer station in Garner, East Wake transfer station in Raleigh). These facilities were selected because of their availability for visitation; a large number of other facilities were contacted but visitation was not possible. All the visited facilities transferred waste into open-top trailers. Tipping floor degradation was observed in all facilities. All floors had cement-paste binder degradation (or aggregate exposure) meaning that the cement-paste binder phase of concrete was attacked, deteriorated, and removed from the concrete, exposing coarse aggregates. The cement-paste degradation issue was most severe at locations where waste was in contact with the floor for a longer duration (where moist waste was piled up). Figure 2.1 shows a photograph of a concrete floor with cement-paste degradation where coarse aggregates are exposed.

Figure 2.1: Typical cement paste degradation of concrete floor at a WTS.

Another notable observation was the degradation of cement paste observed in the long-haul truck loading area (Figure 2.2). These areas are continuously exposed to leachate with minimal exposure to mechanical abrasion. While the long-haul trucks wait for loading, leachate leaks from the trucks. While these concrete floors are subjected to the abrasion due to friction with the truck tires, this abrasion is negligible compared to abrasion on the tipping floor due to scraping by loaders.

The cement-paste degradation is undesirable not only because it reduces the service life of the concrete tipping floor, but also because the resulting abrasive surface increases equipment maintenance cost, e.g., loader tires and rubber pads. Specifically, exposure of the coarse aggregates results in higher wear of rubber tires as reported by an operator during an interview. The observations reported herein were common in all visited WTSs.

(a)

(b)

Figure 2.2: (a) Photograph of the loading area; (b) photograph of the floor of the loading area with cement-paste degradation.

## 2.2. Survey

An internet-based survey was designed and performed using Qualtrics (qualtrics.com). The interviews performed during multiple WTS visits were used to develop appropriate survey questions. In selecting survey questions, the research team also consulted with Mr. Stacey Smith (from Smith Gardner Inc.). The survey consisted of 8 sections and a total 49 questions. The survey questions are included in Appendix A. The survey was disseminated in collaboration with EREF. Despite our best efforts, participation was sparse. A total of 86 responses were received out of which only 22 participants fully completed the survey. A summary of the results is presented in this section.

Figure 2.3 shows the location of the WTSs that provided a completed survey. Surveys that did not include the facility location (e.g. zip code) are not included in Figure 2.3. The service life of WTSs surveyed is provided in Figure 2.4. The average service life of the tipping floor is 8 years. The results indicate that three WTSs have shown a significantly longer service life (over thirteen years) and a large number of waste transfer stations have shown very short (below 5 years) service life. It is noted that the reported service life by owners or operators of the facilities is rather subjective and depends on the management practices as some facilities may delay the repairs longer than others.

Further analysis of the results of the survey is described below and the detailed survey results are provided in Appendix B.

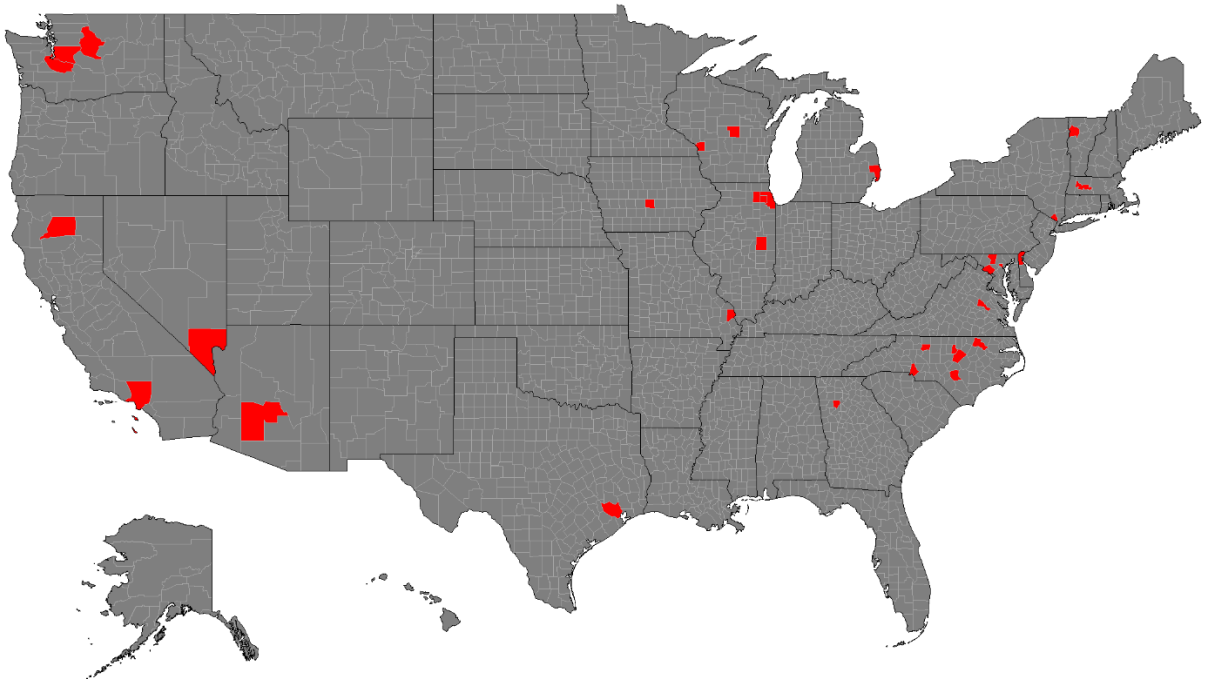


Figure 2.3: WTS survey participants by zip code at county level.

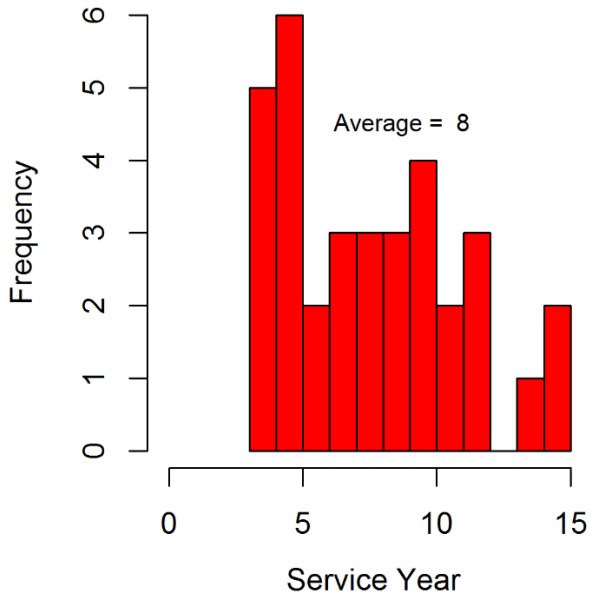



Figure 2.4: WTS tipping floor service life.

## 2.3. Summary of the findings from site visits, interviews and survey

The major observations based on the site visits, interviews and survey results are as follows:

1. The main contributing factors to the degradation of WTS floors are exposure to fresh solid waste leachate and mechanical abrasion by waste handling equipment.
2. Daily washing of the tipping floors prolongs their service life.
3. The service life of the tipping floor was influenced by the amount of waste handled (tons/day) and duration of operation (hours/day and days/week).
4. Waste transfer stations with a longer tipping floor service life, replace loader bucket protection rubber and loader tires less frequently. This may be due the fact that the service life of the floor and the bucket protection rubber are both influenced by the amount of force excreted by the loader (mechanical abrasion).
5. The "time-for-repair" is selected based on visual observations rather than engineering estimates or quantitative measures.

## 2.4. Chemical Analyses of Fresh Leachate and Formulation of Synthetic Leachate

Analytical results are presented in Table 2-1 and the corresponding methods are presented in Chapter 5 (Section 5.1). The data indicate that the leachate solutions mainly consist of three VFAs: acetic, propionic, and butyric. The concentrations of the rest of the organic acids are relatively small. Based on the results in Table 2-1, the synthetic waste leachate solution with the chemical composition shown in Table 2-2 was formulated. To match the pH of the synthetic solution with the average pH of field leachate samples, the pH of the synthetic solution was adjusted to 4.7 by adding sodium hydroxide. The chloride and sulfate ions with the same concentration as those of the field leachate samples were added to the synthetic solution using sodium chloride and sodium sulfate.

Table 2-1: Results of chemical analyses on 20 samples of transfer station leachate from 3 different sites.

| Sources | pH* | Volatile Fatty Acids (VFAs) | | | | | | | | Anions | | Carbon | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Acetic | Propionic | Butyric | i-Butyric | i-Valeric | Valeric | i-Caproic | Hexanoic | Sulfate ($SO_4^{2-}$) | Chloride ($Cl^-$) | From VFAs | Total | VFAs/Total (%) |
| residents | 4.9 | 1123 | 685 | 4149 | 31 | 43 | 0 | 8 | 313 | 1289 | 433 | 3287 | 9315 | 35 |
| commercial | 4.2 | 1905 | 307 | 300 | 14 | 18 | 48 | 7 | 14 | 434 | 50 | 1135 | 9967 | 11 |
| residents | 4.9 | 2330 | 2289 | 3650 | 33 | 48 | 0 | 11 | 102 | 1139 | 914 | 4152 | 7228 | 57 |
| residents | 6.3 | 2458 | 1147 | 350 | 17 | 31 | 69 | 7 | 17 | 597 | 334 | 1815 | 8200 | 22 |
| residents | 4.8 | 2630 | 73 | 104 | 13 | 19 | 6 | 7 | 8 | 1341 | 299 | 1174 | 30375 | 4 |
| commercial | 4.3 | 2792 | 114 | 141 | 5 | 7 | 12 | 2 | 9 | -** | -** | 1270 | 21612 | 6 |
| residents | 4.3 | 2896 | 854 | 207 | 11 | 14 | 31 | 4 | 23 | 1011 | 249 | 1735 | 14658 | 12 |
| school | 4.8 | 4553 | 291 | 420 | 14 | 18 | 25 | 5 | 13 | 1488 | 131 | 2236 | 28576 | 8 |
| commercial | 5.3 | 2413 | 187 | 176 | 12 | 18 | 40 | 10 | 22 | 1864 | 661 | 1213 | 12541 | 10 |
| residents | 5.6 | 2849 | 1369 | 1862 | 108 | 167 | 699 | 11 | 549 | 911 | 102 | 3737 | 5356 | 70 |
| commercial | 4.6 | 2880 | 315 | 196 | 10 | 15 | 28 | 8 | 28 | 626 | 175 | 1465 | 9043 | 16 |
| residents | 5.1 | 3003 | 714 | 390 | 9 | 15 | 128 | 3 | 39 | 453 | 153 | 1876 | 7078 | 27 |
| commercial | 4.7 | 3258 | 173 | 218 | 5 | 8 | 60 | 3 | 212 | 938 | 257 | 1626 | 12020 | 14 |
| commercial | 4.2 | 4039 | 387 | 441 | 24 | 33 | 47 | 11 | 36 | 1424 | 116 | 2134 | 11250 | 19 |
| residents | 4.7 | 4044 | 710 | 636 | 31 | 36 | 114 | 10 | 48 | 991 | 354 | 2451 | 18457 | 13 |
| residents | 4.1 | 4801 | 715 | 666 | 32 | 41 | 75 | 9 | 21 | 1852 | 200 | 2735 | 10873 | 25 |
| residents | 3.9 | 5002 | 208 | 264 | 18 | 23 | 9 | 7 | 22 | 3195 | 918 | 2293 | 25066 | 9 |
| residents | 4.6 | 5955 | 215 | 265 | 29 | 46 | 20 | 7 | 24 | 2355 | 482 | 2705 | 14784 | 18 |
| residents | 4.7 | 6168 | 215 | 265 | 34 | 35 | 27 | 1 | 24 | 1058 | 307 | 2787 | 13271 | 21 |
| residents | 4.3 | 7069 | 979 | 856 | 26 | 33 | 227 | 6 | 80 | 1180 | 544 | 3991 | 23238 | 17 |
| Average | 4.7 | 3608 | 597 | 778 | 24 | 33 | 83 | 7 | 76 | 1271 | 351 | 2291 | 14645 | 16 |
| Mean*** | 4.7 | 2949 | 351 | 325 | 18 | 27 | 35 | 7 | 24 | 1139 | 299 | 2185 | 12281 | 18 |
| STD | 0.5 | 1514 | 530 | 1109 | 21 | 33 | 151 | 3 | 128 | 662 | 248 | 914 | 7238 | - |

The unit of VFAs, sulfate, chloride, and carbon data is mg/l.

* pH values were measured at the site.

** Insufficient sample volume for analysis.

*** Mean values are used for reproducing leachate solution

Table 2-2: Composition and properties of the synthetic waste leachate.

| | |
|---|---|
| Composition | Acetic (2.95 g/l)<br>Propionic (0.35 g/l)<br>Butyric (0.32 g/l)<br>Sodium chloride (1.88 g/l)*<br>Sodium sulfate (0.44 g/l)**<br>Sodium hydroxide (1.20 g/l)*** |
| pH | 4.7 |

* 1139 mg of $Cl^-$ $\times \frac{58.45 \text{ g/mol of NaCl}}{35.45 \text{ g/mol of } Cl^-}$ = 1.88 g/l

** 229 mg of $SO_4^{2-}$ $\times \frac{142.04 \text{ g/mol of } Na_2SO_4}{96.06 \text{ g/mol of } SO_4^{2-}}$ = 0.44 g/l

*** To adjust pH to 4.7

## 2.5. Abrasion tests on cement paste and concrete

This section presents the results of abrasion tests on cement and concrete in the *absence* of exposure to leachate. The corresponding test methods are presented in Chapter 5, Section 5.2 and the materials are described in Chapter 5, Section 5.3.

Figure 2.5 illustrates the results of the abrasion test on cement pastes with different w/c. The results are shown in terms of average volume loss (abraded volume) of three replicates; lower volume loss indicates a higher abrasion resistance. The same data are also reported in Table 2-3. As expected, the abrasion resistance of cement paste decreases with increase of w/c because increase of w/c results in a more porous microstructure. In addition, for w/c below 0.42 (for seal cured condition), unhydrated clinker remains in the cement paste; unhydrated clinker is a hard material, contributing to the abrasion resistance of cement paste.

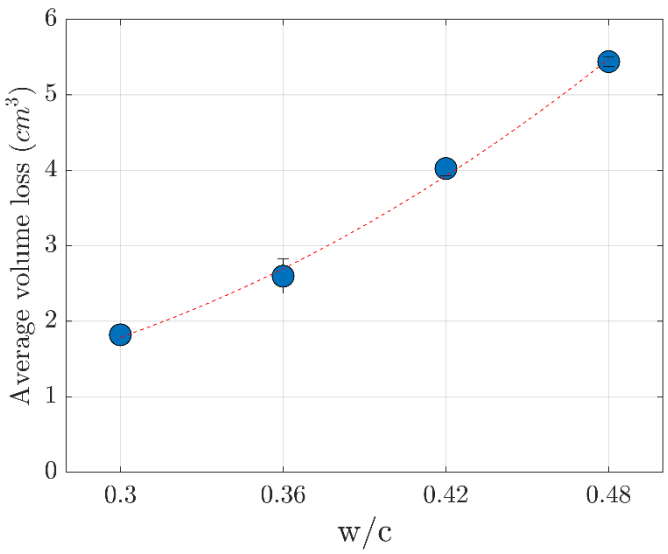



Figure 2.5: Volume loss of cement pastes of different w/c due to mechanical abrasion; smaller abraded volume indicates higher abrasion resistance.

Table 2-3: Abrasion resistance test results for cement pastes of different w/c.

| **w/c** | **Avg. Vol. loss[a] ($cm^3$)** | **SD[b]** | **CoV (%)** |
|---|---|---|---|
| 0.30 | 1.82 | 0.07 | 3.85 |
| 0.36 | 2.60 | 0.23 | 8.85 |
| 0.42 | 4.02 | 0.09 | 2.24 |
| 0.48 | 5.44 | 0.06 | 1.10 |

[a] Average volume loss of 3 replicates
[b] Standard deviation

Figure 2.6 shows the results of abrasion resistance tests on concrete materials with w/c of 0.30 and 0.48, with three different coarse aggregate types (granite, limestone, and their combination). When the abrasion resistance of concrete materials made with the same coarse aggregate type are compared, concrete with the lower w/c always show a higher abrasion resistance. For example, the volume loss of concrete with granite aggregate and w/c = 0.30 (Concr 0.30 Grnt) is smaller than that of concrete with granite aggregate and w/c = 0.48 (Concr 0.48 Grnt). Similarly, the volume loss of concrete with limestone aggregate and w/c = 0.30 (Concr 0.30 Lmst) is smaller than that of concrete with limestone aggregate and w/c = 0.48 (Concr 0.48 Lmst).

However, when the aggregate type is not the same between two concrete materials, the effect of w/c is not significant. For example, concrete with granite aggregate and w/c = 0.48 (Concr 0.48 Grnt) has a smaller volume loss as compared to those of concrete with limestone aggregate and w/c = 0.30 (Concr 0.30 Lmst) and concrete with a combination of granite and limestone aggregate and w/c = 0.30 (Concr 0.30 Grnt\&Lmst). Similarly, volume loss of concrete with a combination of granite and limestone aggregate and w/c = 0.48 (Concr 0.48 Grnt\&Lmst) is smaller than that of concrete with limestone aggregate and w/c = 0.30 (Concr 0.30 Lmst). These data along with the data in Figure 2.5 (which shows lower abrasion resistance with increase of w/c for cement paste) suggests that, the effect of w/c on the abrasion resistance of concrete is secondary to that of coarse aggregate type, or more specifically, coarse aggregate hardness.

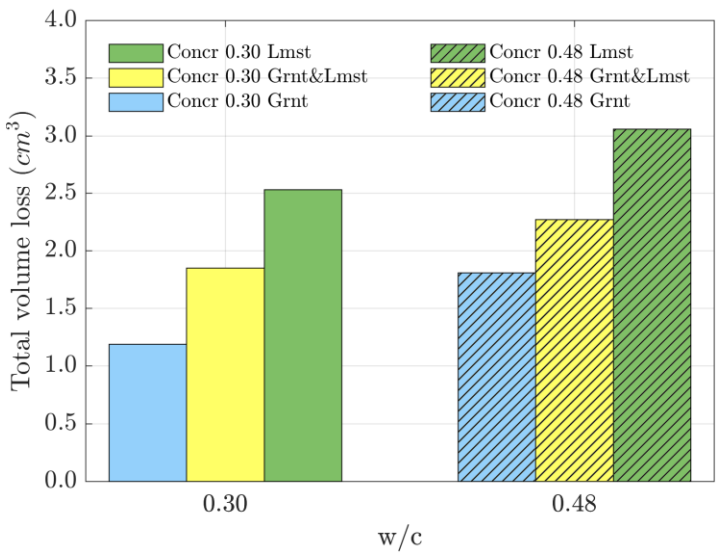



Figure 2.6: The effect of coarse aggregate type and w/c on the abrasion resistance of concrete.

Figure 2.7 shows the results of abrasion tests on concrete materials with w/c = 0.30, and coarse granite aggregates. Concrete materials with three different volume fractions of total aggregates have been tested. The data indicates that the abrasion resistance of concrete decreases rapidly with the decrease of total aggregate volume.

The volume loss of concrete with 70% aggregate and w/c = 0.48 (Concr 0.48 Grnt from Figure 2.6) is 1.80 $cm^3$; the volume losses of concrete materials with w/c = 0.30 containing 40% and 55% aggregate (Concr 0.30 Grnt/40 and Concr 0.30 Grnt/55 in Figure 2.6) are, respectively, 3.88 and 2.77 $cm^3$. Similarly, volume loss of concrete with 70% volume of combined granite and limestone aggregates (hard and soft aggregates) and w/c = 0.48 (Concr 0.48 Grnt\&Lmst) (Figure 2.6) is 2.27 $cm^3$ which is smaller than those of concrete materials with w/c = 0.30

containing 40% and 55% granite aggregate, respectively 3.88 and 2.77 $cm^3$, (Concr 0.30 Grnt/40 and Concr 0.30 Grnt/55 from Figure 2.6). These data show that the effect of aggregate volume fraction is more significant that the effect of w/c.

In Figure 2.6, The volume loss of concrete with limestone aggregate and w/c = 0.48 (Concr 0.48 Lmst) is 3.06 $cm^3$ which is smaller than that of concrete with w/c = 0.30 containing 40% granite aggregates (Concr 0.30 Grnt/40 in Figure 2.6) which is 3.88 $cm^3$, but larger than that of concrete with w/c = 0.30 containing 55% granite aggregates (Concr 0.30 Grnt/55 in Figure 2.6). Therefore, the effect of coarse aggregate type and volume fraction can overshadow the effect of w/c.

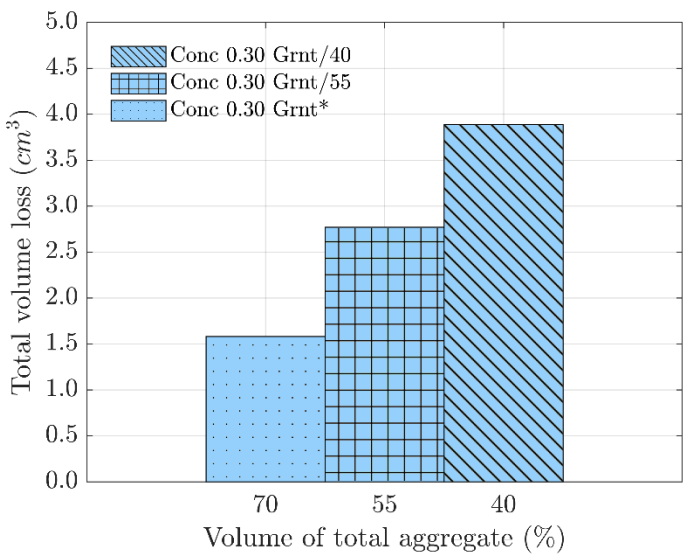



Figure 2.7: The effect of coarse aggregate volume on the abrasion resistance of concrete with w/c = 0.30 and granite coarse aggregates.

The above results indicate that in developing an abrasion resistance concrete, in addition to the type of coarse aggregates, the volume fraction of coarse aggregates is very important and increasing the volume fraction of coarse aggregates will increase the abrasion resistance of concrete. This is in contrast to the current recommendation for the minimum cement content from the Portland Cement Association (PCA) manual [46].

In Figure 2.8 we have plotted the 28-day abraded volume for concrete with different w/c, aggregate type, and aggregate volume fractions in bar chart corresponding to left y-axis. Along with these data, we have plotted the 28-day compressive strength of these materials on the right y-axis. Clearly, no correlation exists between compressive strength and abrasion resistance of concrete.

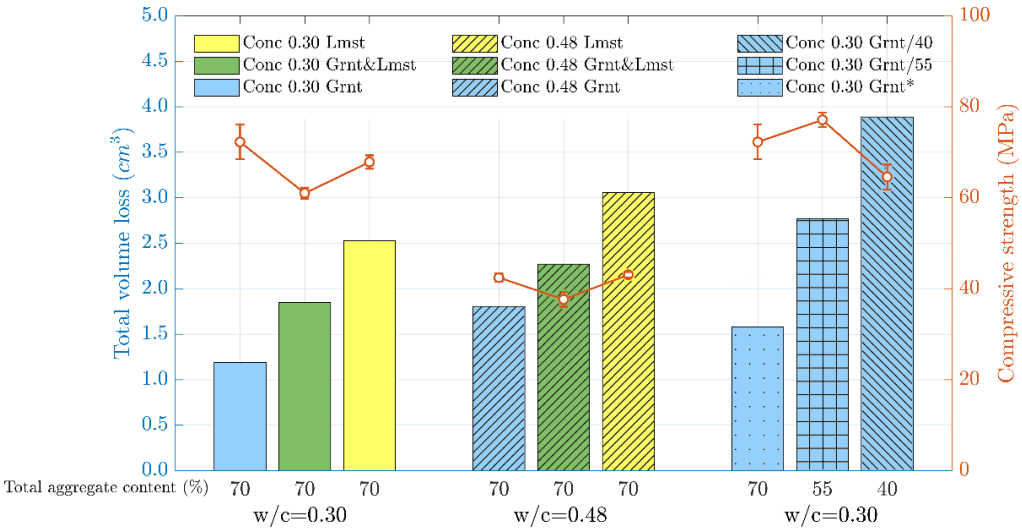



Figure 2.8: Abrasion resistance and compressive strength for concrete.

## 2.6. Summary of findings from abrasion tests on cement paste and concrete in the absence of exposure to leachate

Our findings indicate that (i) the abrasion resistance of concrete is primarily controlled by the hardness and the volume fraction of the coarse aggregates; (ii) decreasing w/c of mixture may increase the abrasion resistance of concrete but its effect is, in general, smaller than those of coarse aggregate hardness and volume fraction; (iv) no general correlation exits between w/c and the abrasion resistance; and (v) in general, no correlation exists between compressive strength and abrasion resistance.

## 2.7. Simultaneous attack of the leachate and mechanical abrasion

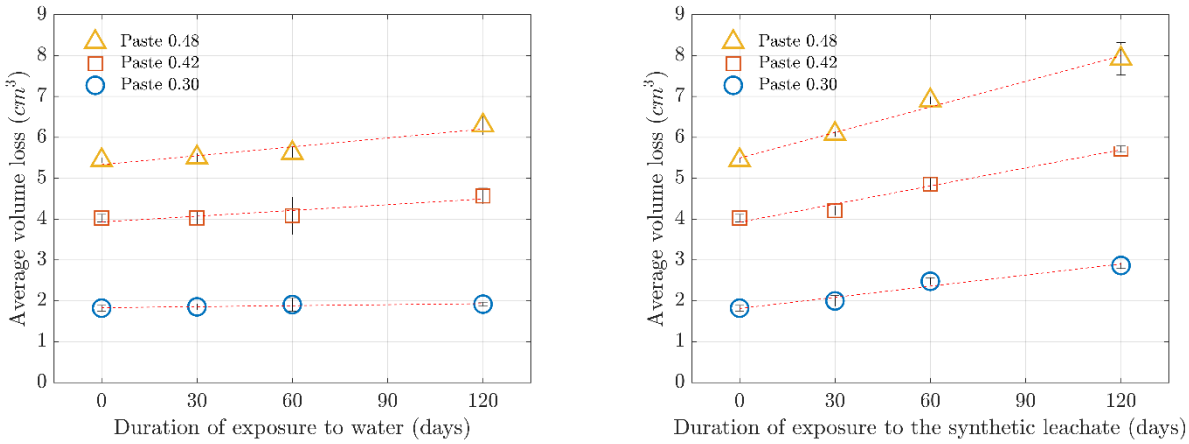
This section presents the results of abrasion tests on cement and concrete after exposure to leachate. For the test method, please see Chapter 5, Section 5.2 and for materials see Chapter 5, Section 5.4.

Figure 2.9 illustrates the results of the abrasion tests performed on cement pastes exposed to deionized water (Figure 2.9a) and the synthetic leachate solution (Figure 2.9b). Exposure to deionized water was used as reference since the synthetic leachate solution contains water. The results are shown as average volume loss of three replicates and the error bars indicate the standard deviation.

Cement paste materials with higher w/c have a higher initial volume loss (at zero day exposure). When exposed to water (Figure 2.9a) all cement pastes show a slight increase in volume loss. The rate of volume loss over time (slope of the lines) increases with w/c and the rate of volume loss for the cement paste with w/c = 0.30 is approximately zero.

In Figure 2.9b, the rates of the volume loss (slope of the lines) of the cement paste materials exposed to the synthetic leachate solution is significantly higher than those of cement pastes exposed to water; even cement pastes with w/c = 0.30 shows an increased volume loss with exposure time. The rate of volume loss increases significantly with w/c.

When exposed to water, the slight increase of volume loss is mainly due to the dissolution and leaching of CH. However, when exposed to the synthetic leachate solution, in addition to leaching of CH, the reduction in the pH of the cement paste pore solution is significant, resulting in the degradation of CSH. This degradation of CSH results in softening and decrease of abrasion resistance.




(a) (b)

Figure 2.9: The effect of w/c ratio on the abrasion resistance of cement paste specimens after exposure to the synthetic leachate and water for 0, 30, 60, and 120 days (smaller abraded volume is better): (a) water and (b) synthetic leachate.

Figure 2.10 shows the effect of polymeric fiber and the chemical surface hardener on the abrasion resistance of cement paste. The left and right columns show the results for cement pastes with w/c = 0.30 and w/c = 0.42, respectively. The first row corresponds to the effect of fibers, and the second row corresponds to the effect of chemical surface hardener.

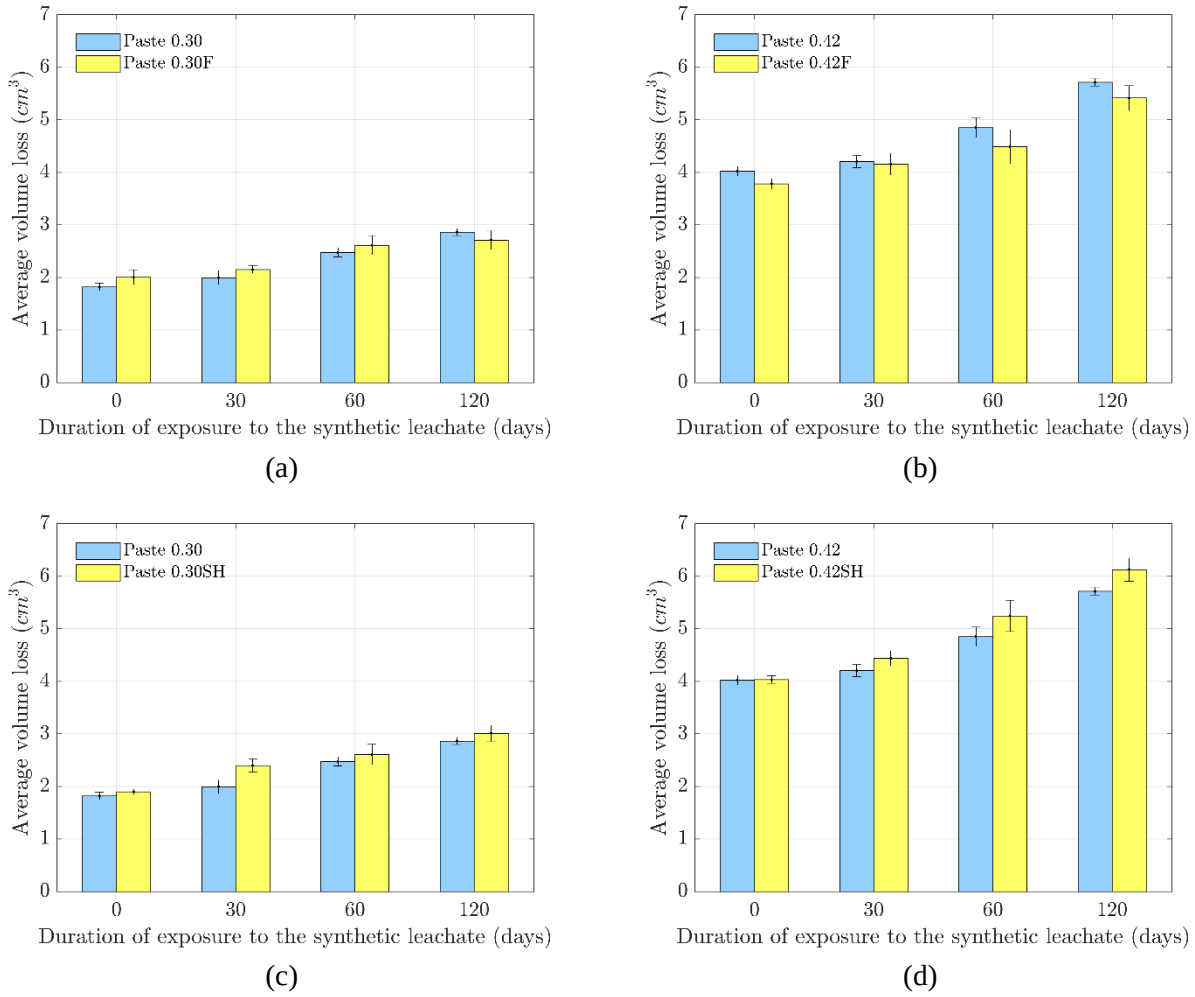
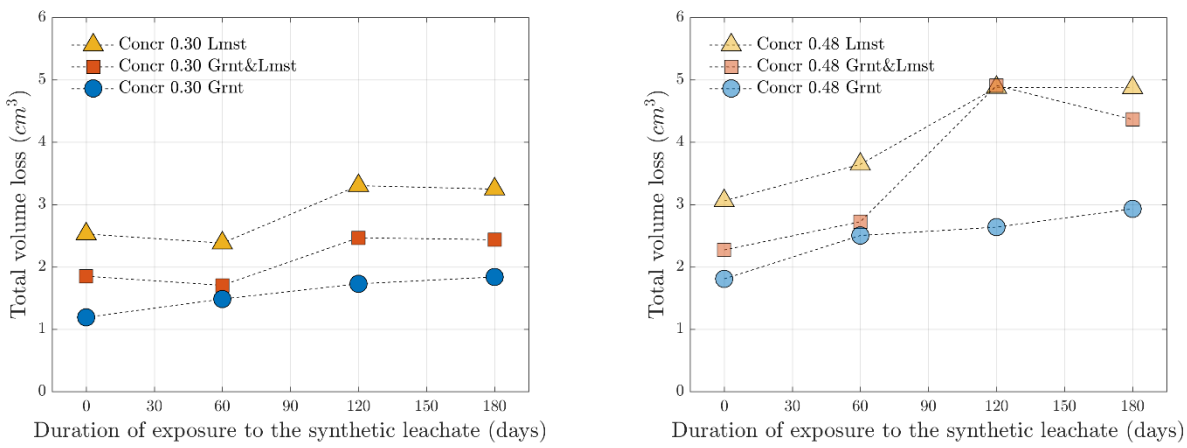



Figure 2.10: The effect of fibers and chemical surface hardener on the abrasion resistance of cement paste after exposure to the synthetic leachate for 0, 30, 60, and 120 days: (a) w/c=0.30 + fibers; (b) w/c=0.42 + fibers; (c) w/c=0.30 + surface hardener; and (d) w/c=0.42 + surface hardener.

Figure 2.10a indicates that the addition of fibers, has a negligible effect on increasing the abrasion resistance of cement paste with w/c = 0.30; in fact, it may adversely affect the abrasion resistance although the adverse effect is negligible. Figure 2.10b however, indicates that the addition of fibers increases the abrasion resistance of cement paste with w/c = 0.42. The reason for the difference between the two cases, is that in low w/c cement paste, paste contributes more to the abrasion resistance as compared to fibers since the cement paste is harder; or since fibers are significantly softer than the matrix, the addition of fibers does not have a significant effect on abrasion resistance or they may even degrade the abrasion resistance. On the other hand, when fibers are included in a soft matrix (high w/c) they may help in holding the matrix together during the mechanical abrasion. Based on these results, it seems that fibers may be effective in increasing the abrasion resistance of pastes with high w/c but they may not be effective for low w/c cement pastes.

Figure 2.10c and Figure 2.10d both indicate that the use of chemical surface hardener has a negligible effect on the abrasion resistance of cement paste (zero day exposure) and reduces the abrasion resistance of cement paste exposed to organic acid attack. The rate at which the use of chemical surface hardener reduces the abrasion resistance increases with w/c; in other words, the use of chemical surface hardener degrades the abrasion resistance of high w/c pastes more than those of low w/c pastes. The reason for the reduction in the abrasion resistance when exposed to the synthetic leachate is that this chemical surface hardener converts CH to CSH; since CH provides buffer against acid attack, this conversion reduces the resistance of cement paste treated with the chemical surface hardener. It should be noted that the vast majority of the chemical surface hardeners work by converting CH to CSH and will likely result in the same effect.



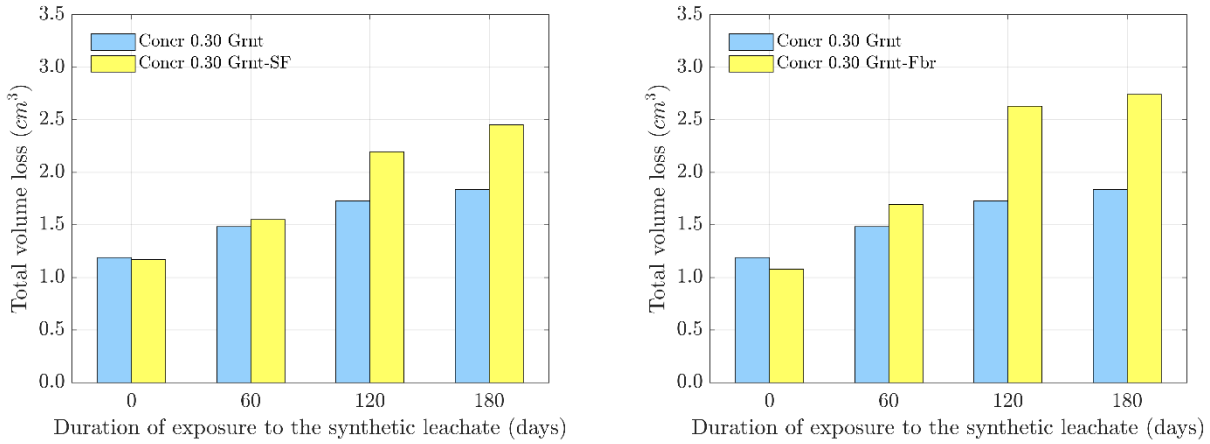

(a) (b)

Figure 2.11: The effect of exposure to the synthetic leachate on the abrasion resistance of concrete with different aggregate types: (a) w/c 0.30 and (b) w/c 0.48.

Figure 2.11 shows the effect of coarse aggregates on the abrasion resistance of concrete exposed to the synthetic leachate solution. The graphs on the left and right, respectively, correspond to concrete materials with w/c=0.30 and 0.48. As discussed in Section 2.5, in the absence of organic acid attack, the abrasion resistance of concrete is mainly influenced by the hardness of coarse aggregate and the effect of w/c ratio is secondary. However, when the simultaneous organic acid exposure and mechanical abrasion is concerned, the effect of w/c becomes very significant. Comparing the results in Figure 2.11a and Figure 2.11b, shows that at both w/c of 0.30 and 0.48, the abrasion resistance of concrete decreases with exposure to the synthetic leachate solution but this decrease is more pronounced at higher w/c; the decrease of abrasion resistance is especially significant when concrete contains soft aggregate (limestone in this case).

Overall, concrete materials containing only granite aggregate show a significantly better abrasion resistance in the presence or the absence of organic acid attack as compared to concrete materials containing limestone aggregates. Concrete materials that have both limestone and granite aggregates seem to show a comparable abrasion resistance to concrete materials that are made of granite aggregates up to 60 days of exposure to the synthetic leachate solution, however, their abrasion resistance decreases significantly over long term exposure. This seems to suggest that limestone may provide only a short-term buffer against organic acids.

Figure 2.12a and Figure 2.12b show the results of abrasion resistance tests performed on concrete materials containing silica fume and fibers, respectively. In Figure 2.12a, in the absence of organic acid attack (zero day exposure), the use of silica fume does not affect the abrasion resistance of concrete or slightly improves it; this is consistent with the previously reported results in the literature [58] (Chapter 1). However, in the presence of organic acid exposure, the abrasion resistance of concrete containing silica fume decreases as compared to that of concrete that does not contain silica fume. This is because silica fume converts CH to CSH, reducing the buffer capacity of concrete against acid attack.



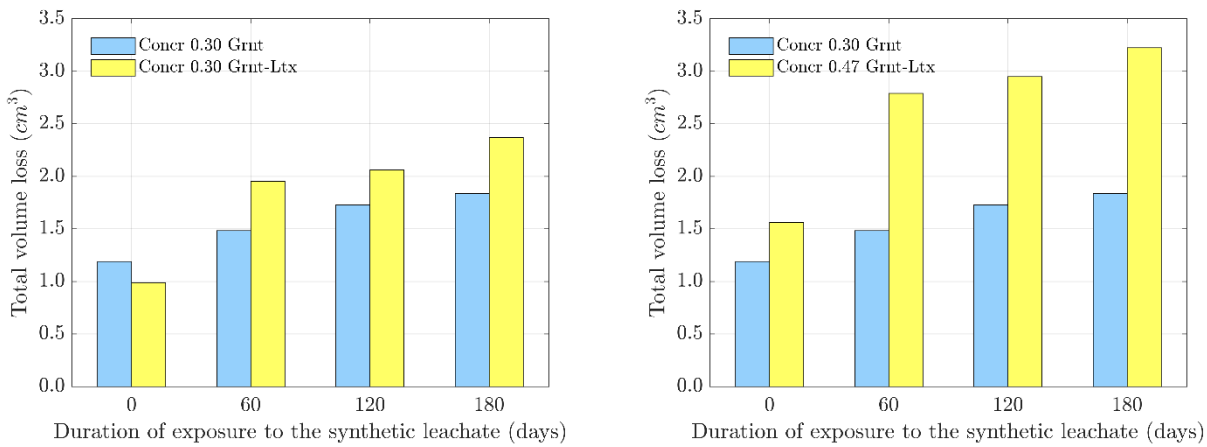

(a) (b)

Figure 2.12: The effect of silica fume and polymeric fibers on the abrasion resistance of concrete after exposure to the synthetic leachate: (a) silica fume, (b) polymeric fibers.

Figure 2.12b compares the abrasion resistance of concrete containing fibers (fiber reinforced concrete) with plain concrete. Similar to the previous results reported in the literature [8,23], in the absence of organic acids, the use of fibers increases the abrasion resistance of concrete; however, after exposure to organic acids, the abrasion resistance of fiber reinforced concrete decreases more than that of unreinforced concrete. The use of fibers in low w/c cement paste (w/c = 0.30) also showed a decrease in abrasion resistance (a) but to a lesser extent. The reason

for the more significant decrease in the abrasion resistance of concrete as compared to cement paste may be attributed to the higher fiber-to-cement paste volume fraction ratio in concrete as compared to cement paste since only 30% of the concrete is made of cement paste; the fiber to cement paste volume ratio of concrete is 1.5% which is higher than that of fiber reinforced cement paste as 1.0%.

Figure 2.13a and Figure 2.13b show the effect of latex on the abrasion resistance of concrete. The water content of the mixture in Figure 2.13a has been adjusted to keep the w/c of the mixture at 0.30 while the water content of the mixture in Figure 2.13b has not been adjusted but the ratio of the mixing water to cement is kept at 0.30; this resulted in the true w/c = 0.47.




(a) (b)

Figure 2.13: The effect of latex on the abrasion of concrete after exposure to the synthetic leachate: (a) w/c 0.30, and (b) w/c 0.47.

In the absence of leachate exposure, the use of latex in concrete, when the w/c is kept constant, the abrasion resistance of concrete increases; this is consisted with the previous results reported in the literature [43]. When the w/c is not kept constant, the abrasion resistance of concrete decreases (b). In the presence of leachate exposure, however, the abrasion resistance of concrete containing latex decreases; this decrease is significantly more for higher w/c concrete (or in this case when water content has not been adjusted). The decrease of abrasion resistance with addition of latex, may be due to the chemical interaction between organic acids and latex.

Figure 2.14 shows the effect of surface washing on the abrasion resistance of concrete with w/c=0.30, and coarse granite aggregate. The specimens were exposed to the synthetic leachate solution and then were rinsed washed every other day for a total of 120 days. Tap water and saturated calcium hydroxide solutions were used for washing.

The volume losses of rinsed specimens were higher than unrinsed specimens. The reason is that water and $Ca(OH)_2$ solution dissolved calcium salts on the specimens' surface. Calcium salts are formed from reaction between calcium phases in concrete and organic acids [50]. These salts may hinder the penetration of the synthetic leachate solution into the specimens. However, when rinsed, the salts dissolve and wash away, the new surface layer is better exposed to the synthetic leachate solution resulting in more aggressive acid attack. The reason for more volume loss in the specimen washed with $Ca(OH)_2$ solution than the specimen washed with water is unclear. The result in Figure 2.14, however, is not consistent with the survey result; the facilities that regularly wash the concrete floor have a longer service life. We believe that our testing condition cannot successfully mimic the actual field conditions.

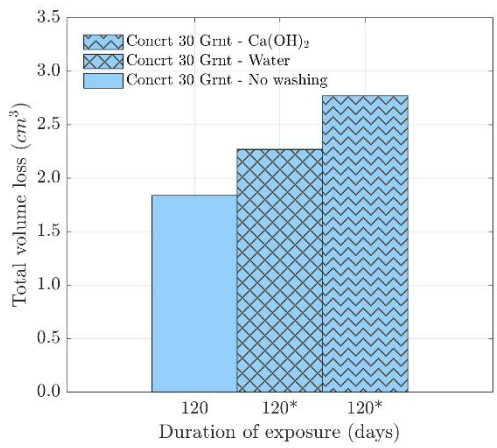



Figure 2.14: The effect of rinsing specimens with calcium hydroxide and water on the abrasion resistance of concrete with w/c = 0.30 and granite coarse aggregates.

Figure 2.15 shows the results of abrasion testing on concrete (containing granite coarse aggregate) and mortar (no coarse aggregate) mixtures. The results in Figure 2.15 indicate that the use of coarse aggregate is essential and significantly contributes to abrasion resistance.

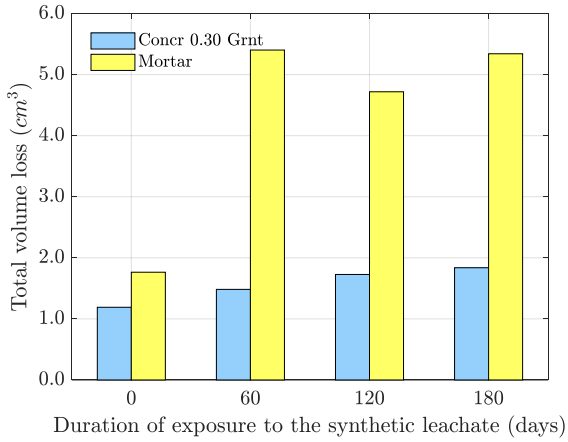



Figure 2.15: The effect of aggregate size on the rate of abrasion of concrete.

## 2.8. Summary of findings on the simultaneous attack of the leachate and mechanical abrasion

We investigated the effect of leachate exposure on the abrasion resistance of concrete with the goal of understanding whether the available knowledge on the abrasion resistance of concrete applies directly to the abrasion resistance of concrete exposed to waste leachate organic acids. The results indicate that factors that increase the abrasion resistance of concrete in the absence of organic acid attack may or may not increase the abrasion resistance of concrete exposed to leachate.

In the absence or presence of organic acid attack (from leachate), the abrasion resistance of concrete is mainly a function of hardness of the coarse aggregates; if hard coarse aggregates (granite herein) are used in production of concrete, w/c plays a secondary role in increasing the abrasion resistance of concrete. On the other hand, if soft aggregate that are reactive with organic acids (limestone herein) are used, w/c has a significant effect on the abrasion resistance of concrete exposed to organic acids.

While limestone reacts with organic acids, it only provides a short-term buffer against organic acids and the abrasion resistance of high w/c concrete materials containing limestone aggregates decrease very rapidly in long-term exposure to organic acids.

While the use of silica fume, polymeric fibers, and latex increase the abrasion resistance of concrete in the absence of organic acid attack from leachate, they decrease the abrasion resistance of concrete exposed to organic acids. Silica fume coverts CH to CSH, reducing the buffer capacity of the concrete against organic acids; polymeric fibers are softer than cement paste and in presence of organic acids may suffer from weak interface and may pull out; and latex may react with organic acids resulting in the decrease of abrasion resistance of concrete.

# 3

# Material Design Recommendations for WTS's Floor

A. General

1. The placing, finishing, and curing of the concrete tipping floor for solid waste transfer stations should adhere to the requirements of this chapter and per the details provided on the contract drawings. The concrete floor shall be placed on top of the building structural floor or compacted gravel.
2. The current section only provides materials, placing, finishing, and curing requirements and recommendations for the cast-in-place concrete due to the exposure to leachate during operation. In addition to the requirements of the current section, the concrete tipping floor shall meet the requirements and specifications for structural design in accordance with the most recent provisions of the Building Code Requirement for Structural Concrete (ACI 318).
3. The concrete tipping floor shall have a minimum thickness of 6 inches (~152 mm).

B. Cement

1. Unless otherwise specified or shown on the plans, concrete shall be made with the Portland cement conforming to ASTM Specification C-150, Type I or Type II. Portland cement conforming to the requirements of both types is also acceptable (i.e., Type I/II). The same brand and type of cement shall be used throughout the entire project.

C. Aggregates

1. General: All aggregates shall conform to requirements of ASTM C 33 and shall be sound aggregates according to ASTM C 88. Aggregate sources with documented or known history of alkali silica reactivity shall not be used.

2. Fine Aggregate

   (1) Washed fine aggregate shall consist of clean, hard, durable, uncoated particles of sand. It shall be free from dust mica, shale, alkali, organic matter, loam, soft or flaky particles.

   (2) Deleterious Substances - The fine aggregate shall not contain clay lumps and shall not contain more than half a percent (0.50%) by weight of material removed by decantation.

   (3) Grading - Fine aggregate shall conform to the requirements of ASTM C 33 with percent passing 75-□m (No. 200) not exceeding 3%.

3. Coarse Aggregate

   (1) Type of Aggregate – Siliceous aggregate, for example, granite or gravel shall be used. Carbonate aggregate, for example, limestone or dolomite shall not be used. Granite coarse aggregate is the most recommended aggregate type.

   (2) Composition and Quality - Coarse aggregate shall be washed and shall consist of similar chemical component, hard, tough, uncoated, and durable particles. It shall contain no vegetable matter or soft, flaky, thin, or elongated particles. Deleterious substances shall not exceed the following amounts:

      1. Soft fragments..... 0.20%
      2. Coal and lignite ..... 0.25%
      3. Clay lumps..... 0.25%
      4. Material passing No. 200 Sieve ..... 1.50%
      5. Thin or elongated pieces (length greater than 5 times the average thickness) 10 %

4. Grading - Coarse aggregate shall be well graded between the limits specified by ASTM C33. The maximum aggregate size shall not exceed one third the minimum slab thickness.

D. Water

1. The water used in mixing and curing concrete shall be fresh, clean, potable and free from oil, acid, alkali, organic matter, and deleterious amounts of chloride ion.

E. Concrete Mixture

1. Water-to-cement (w/c) ratio of the concrete mixture shall not exceed 0.36.
2. The volume of total aggregate shall not be less than 70%.
3. Pozzolanic additives including fly ash, silica fume, slag, metakaolin, calcined clay shall not be used.
4. Fibers shall not be used.
5. Latex modification shall not be used.
6. The concrete mixture shall contain air-entraining admixture and shall have the minimum air content appropriate for the exposure condition.
7. The concrete mixture shall contain high range water reduce (superplasticizer).
8. The concrete mixture shall contain shrinkage reducing admixture.
9. The concrete shall meet all the requirements for structural design including the minimum required strength.

F. Concrete Admixtures

1. The high range water reducer admixture shall conform to ASTM C 494, Type F.
2. The shrinkage reducing admixture shall conform to ASTM C 494, Type S.
3. Air entraining admixtures shall conform to ASTM C 260.
4. All admixtures shall be compatible and have a single manufacturer.
5. Admixtures shall be used only as recommended by the manufacturer and to deliver the specified strength at 28 day. New, unknown, or experimental admixtures are not allowed.
6. Chloride containing admixtures shall not be used.
7. Admixtures formulated to accelerate time of setting shall not be used.

G. Mixing and Delivery

1. The concrete mixture shall have 6 to 8 inch slump measured according to ASTM C 143.
2. All concrete batches shall be consistent, produced using the same materials and the same processing methods. All mixtures shall have a uniform distribution of the materials throughout the mass and shall be uniform in color.
3. Ready mixed concrete shall conform to ASTM C 94.
4. No additional water shall be added to the mixture at the time of placing or finishing.
5. The Contractor shall document and report the slump and air content measurements.

H. Placing

1. The concrete shall be placed starting from one end of the slab and progressively placed in longitudinal direction until the completion at the other end without the formation of cold joints. Control (contraction/expansion) joints shall be placed during the placement of the concrete. Concrete placement shall start from far end of the slab and proceed toward the concrete supply source. The concrete shall be placed as close as possible to its final location.
2. The concrete shall be properly vibrated and consolidated. Excessive vibration that results in aggregate segregation shall be avoided. Vibrators shall not be used to move the mixture in horizontal direction.
3. During the placement, concrete shall be protected against drying. The effective use of methods such as foggers or protecting the mixture against drying using plastic sheets is acceptable.

I. Finishing

1. Slab floor:
   (1) Bullfloating or darbying shall be used immediately after strikeoff and shall be completed before bleed-water accumulates on the surface to obtain flat surface with the specified slope. Aluminum or magnesium alloy bullfloat or darby tools shall be used.
   (2) The bleed-water shall not be worked into the concrete. The bleed-water shall evaporate naturally without accelerating the evaporation rate.
   (3) After bleed-water sheen evaporates and concrete has enough strength, the concrete shall be floated using hand float or machine float (power float). If hand floating is used, magnesium alloy tools shall be used. The drying of the surface moisture before troweling must proceed naturally and must not be hastened by sacking or dusting on of dry sand and cement.
   (4) The slab shall receive steel trowel finish. Steel trowel shall be used to produce a smooth surface free from defects. A second steel troweling shall be done producing a plane, hard, dense, finished surface.
   (5) Chemical surface hardeners shall not be used.

J. Curing

1. Curing Materials
   (1) The water used for curing shall be fresh, clean, potable and free from oil, acid, alkali, organic matter, and deleterious amounts of chloride ion.
   (2) Sheet materials shall conform to ASTM C 171.

(3) Burlap cloth made from jute, kenaf, or cotton mats conforming to AASHTO M 182 shall be used.

K. Procedure

1. Freshly placed concrete shall be protected from wash caused by rain and flowing water.
2. The slab shall be protected against drying immediately after finishing with a layer of plastic sheet membrane conforming to ASTM C 171 for the entire duration of curing.
3. The slab shall be cured for fourteen (14) days using two layers of water saturated burlap and a layer of plastic sheet membrane. During the 14 days of curing the burlap shall be kept water saturated at all times.
4. The slab shall be subjected to natural drying for a minimum of two (2) days prior to the operation of the waste transfer station.

L. JOINTS

1. Construction Joints:

(1) Construction joints will not be permitted except as may be shown on the drawings and on the contractor's approved placement schedule.

(2) If construction joints are not shown on the drawings and are necessary for the progress of the work shall be shown in complete detail and approved by engineer.

2. Contraction/Expansion Joints (Control Joints)

(1) Control joints shall be placed during the placement of the concrete slab.

(2) The control joints shall extend through the entire depth and length of the slab.

(3) The control joints shall be 0.8 in. wide and filled with sealant.

(4) The maximum spacing between control joints shall not exceed the following:

Minimum Control Joint Spacing Requirement (ft)

| **Slab thickness, inch** | **Maximum aggregate size less than ¾ inch** | **Maximum aggregate size ¾ inch and larger** |
|---|---|---|
| 6 | 12 ft | 15 ft |
| 7 | 14 ft | 17 ft |
| 8 | 15 ft | 20 ft |
| 9 | 15 ft | 20 ft |
| 10 | 15 ft | 20 ft |

# 4

# Findings and Concluding Remarks

In this research project (i) a synthetic representative waste leachate solution formulation was developed by performing chemical analyses on a large number of fresh waste leachate samples collected at WTSs, (ii) a new abrasion resistance test method and equipment was developed, (iii) abrasion resistance tests were performed on cement paste and concrete materials of different compositions in the presence and absence of exposure to leachate, and (iv) material design guidelines and recommendations for WTSs' floor were developed.

The developed abrasion test method and equipment can be used to quantify the abrasion resistance of cement paste, mortar and concrete materials with a maximum coefficient of variation of 4.4% which is significantly smaller than that of the existing abrasion test methods.

The results of abrasion tests on cement paste and concrete materials in the absence of exposure to synthetic leachate indicate that (i) the abrasion resistance of concrete is primarily controlled by the hardness and the volume fraction of the coarse aggregates, (ii) decreasing the w/c of the mixture may increase the abrasion resistance of concrete but its effect is, in general, smaller than those of coarse aggregate hardness and volume fraction, (iii) no general correlation exists between w/c and the abrasion resistance; and (iv) no correlation exists between compressive strength and abrasion resistance of concrete.

The results of abrasion tests on cement paste and concrete materials in the presence of exposure to synthetic leachate indicate that (i) the abrasion resistance of concrete is mainly a function of the hardness of the coarse aggregates; (ii) w/c has a significant effect on the abrasion resistance of concrete exposed to organic acids, especially, when soft aggregates that are reactive with organic acids (limestone herein) are used; (iii) limestone coarse aggregates provide only a

short-term buffer against organic acid attack and the abrasion resistance of high w/c concrete materials containing limestone aggregates decreases very rapidly in long-term exposure to organic acids; (iv) while the use of silica fume, polymeric fibers, and latex increases the abrasion resistance of concrete in the absence of exposure to leachate, their use decreases the abrasion resistance of concrete exposed to leachate.

These findings were used to develop guidelines and suggestions for the material design of WTS concrete floors suggesting: (i) the use of w/c lower than 0.36; (ii) the use of a minimum of 70% total aggregate by volume; (iii) the use of granite coarse aggregates which do not react with organic acids; (iv) the avoidance of pozzolanic materials including fly ash, silica fume, slag, or other pozzolanic materials that reduce the amount of calcium hydroxide in concrete; and (v) the avoidance of polymeric fibers and latex modified mixtures.

A PhD student was trained during this project. Two journal papers have been prepared based on the findings. In addition, two conference presentations have been given [59,60]. The research team plans to prepare two articles for relevant trade journals to disseminate the findings of this research among practicing engineers. The research team would like to disseminate the findings of this project through an EREF webinar if deemed appropriate by EREF.

The findings of this research project enable construction of WTS concrete floors with long service life by designing concrete mixtures to protect against the degradation mechanisms involved. The design guide also provides provisions to improve installation methods of WTS concrete floors. While the outcomes of the present research can be used for construction of new floors or resurfacing of large areas of existing floors, these outcomes cannot be used for repair and patching of existing floor. It is hypothesized that exposure to organic acids from leachate will affect the bond strength between concrete and repair materials, resulting in delamination and cracking of repair materials or thin overlays. Further research on repair materials and strategies are needed. The present research only evaluated the performance of conventional concrete materials; further research on the performance of unconventional concrete materials under simultaneous exposure to leachate and mechanical abrasion is needed to enable informed decision making by engineers.

# 5

# Materials and Methods

## 5.1. Chemical Analyses of Fresh Leachate and Formulation of Synthetic Leachate

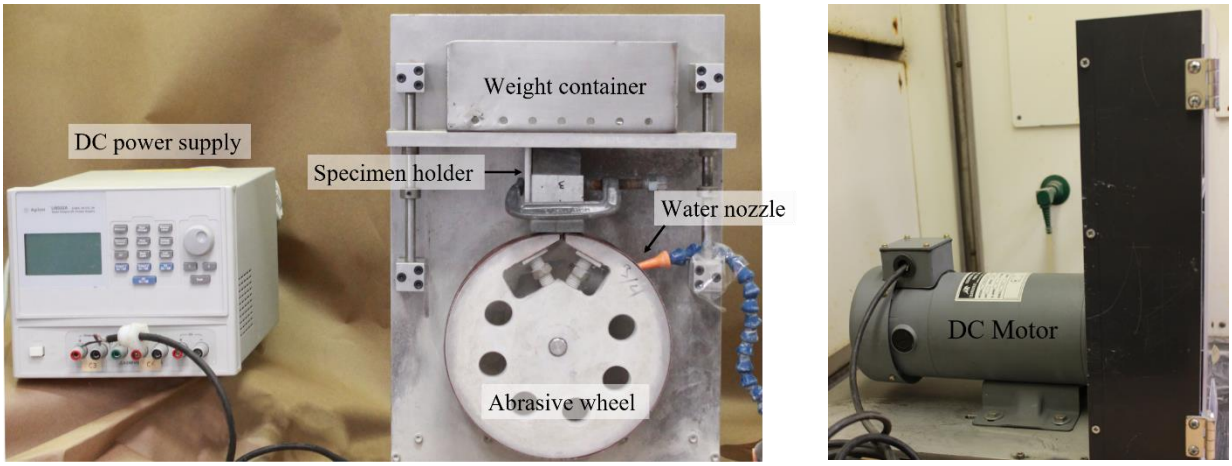
A total of twenty leachate samples were collected from three different WTSs. The pH of the leachate samples was measured on site immediately after collection. The samples were then transported to the laboratory and were preserved by freezing until the start of the chemical analyses. Prior to the chemical analyses, after thawing, the liquid portion of the waste leachate was separated by centrifuging for 45 minutes at 3000 RPM and then filtered.

The solid waste leachate from transfer stations was expected to largely consist of volatile fatty acids (VFAs) [1–4]. Therefore, in the present work, the VFAs were quantified by gas chromatography (GC), and the total organic content in the leachate was estimated by measuring the non-purgeable organic carbon (NPOC). For the GC analysis, 10 ml of each leachate sample was mixed with 85% phosphoric acid to lower its pH to under 2, after which samples were filtered with a 0.2 μm filter. For the NPOC test, leachate samples were filtered with a 0.2 μm filter and then were diluted by a factor of 1000. The effect of dilution was then accounted for in calculating the actual concentration. The concentration of chloride and sulfate ions were quantified using a Dionex ion chromatograph.

## 5.2. The new abrasion test method and equipment

Figure 5.2 shows a photograph of the in-house developed abrasion test equipment (abrasion tester). The abrasion tester consists of a Direct Current (DC) motor that is powered with a DC current supply. The use of DC power supply enables an accurate control of speed of the motor. The specimen is secured in a specimen holder using a C-clamp. In the specimen holder, the specimens sit against a rubber block to minimize vibration during the test which avoids impact to

the specimen.  The specimen rests against the rotating abrasive wheel. Different types of wheels can be used for different materials. The abrasive wheel shown in Figure 5.1 is developed in-house and is made of an aluminum wheel that securely holds an 1-inch thick abrasive tape.



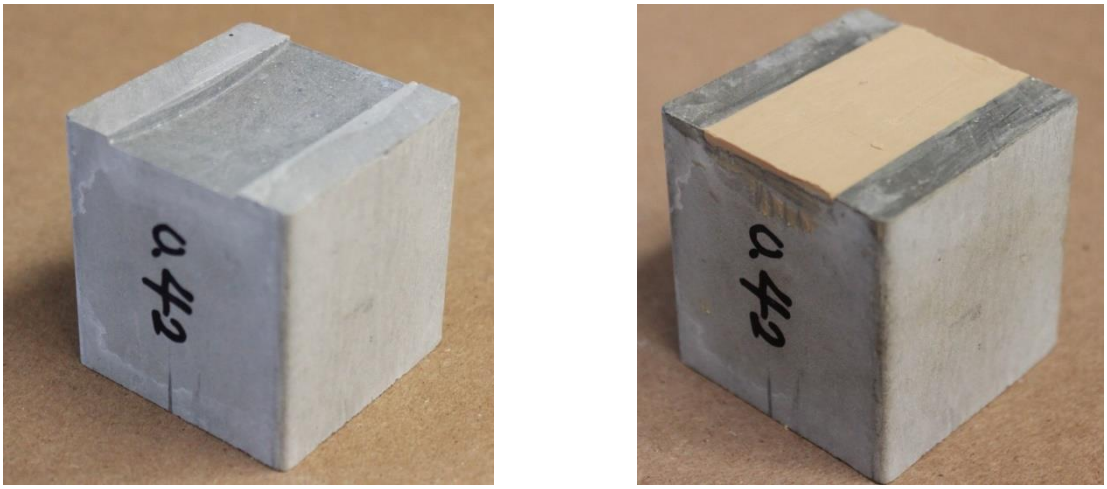

(a) (b)

Figure 5.2: The newly developed test machine: (a) front view and (b) side view.

The specimen is pressed against the wheel by the “weight assembly” above the specimen holder that only allows vertical movement of the specimen. The total self-weight of the weight assembly is 2.6 kg (5.7 lb) and can be increased by placing weights in the “weight container”. The abrasion tester is equipped with a water nozzle to avoid heating of the specimen.

In this research, a 100 grit abrasive tape (Figure 5.2a) was used for cement paste specimens with 190 RPM (corresponding to 18 V) for 2 minutes. The abrasive tape was replaced before each test. The average volume loss of 3 replicates was used as the test result.  For concrete specimens, a commercial silicon carbide grinding wheel with 0.50 inch thickness was used. Concrete specimens were abraded with 420 RPM (corresponding to 40 V) for 5 minutes. Each wheel was used to abrade 3 specimen replicates due to the abrasion of the wheel itself which affects the results.  The sum of their volume losses was used as the abrasion test result for concrete.

The volume loss of specimens were measured using oil base modeling clay as shown in Figure 5.3 following ASTM standard C418 [19]. The mass change before and after applying clay was divided by its density (1.64 g/cm$^3$) to obtain the volume loss. The use of volume loss instead of mass loss eliminates the error from mass gain due to water absorption during the test.




(a) (b)

Figure 5.3: The example of volume loss measurement using oil base modeling clay after an abrasion test on cement paste specimen of w/c=0.42: (a) before and (b) after applying clay.

Using results of a set of experiments, the coefficient of variation (CoV) was estimated to evaluate the repeatability and reliability of the introduced abrasion test method. CoV is the ratio of the standard deviation to the average value of the measurements. In a series of tests on cement pastes with different w/c, CoVs of 3.85, 8.85, 2.24, and 1.10% were obtained; no correlation between CoV and w/c observed; the largest value of 8.85% is believed to be caused by the specimen preparation rather than the test method. A CoV of 4.41% was observed for concrete. These CoV are smaller than those reported for ASTM test methods (typically 6-21% [20–22]); however, the reported values for the new test method are based on a limited number of tests and further testing is required to properly quantify the variability.

## 5.3. Materials: abrasion tests on cement paste and concrete in the absence of exposure to leachate

All cement paste and concrete materials were cast using Type I Ordinary Portland Cement (OPC). All materials were cast in prismatic 2×2×24 inch PVC molds and were cured in sealed condition at room temperature for over 180 days except specimens with total aggregate volume of less than 70% (Table 5-1). After curing, the materials were cut into 2×2×2 inch cubic specimens. The cut surfaces were used in abrasion testing to eliminate the effect of cement paste deposition on the cast surface. Cut surface also more realistically mimics the long-term condition of the floor.

Cement paste specimens had w/c of 0.30, 0.36, 0.42, and 0.48. Concrete specimens were cast using coarse aggregate of granite, limestone, or using their combination. The maximum

aggregate size for concrete was 1/2 inch and the total aggregate content was 70% by volume. The proportions of coarse and fine aggregates, respectively, were 60% and 40% of the total aggregate by volume for all concrete specimens. Concrete specimens had w/c of 0.30 and 0.48. In addition, a set of concrete materials with variable granite coarse aggregate content were cast that had total aggregate volume of 40%, 55%, and 70%. Table 6-2 provides the details of concrete materials tested. Compressive strength tests were conducted on concrete materials following ASTM C1231 [45] where concrete specimens were cast in 4×8 inch cylinders and cured at room temperature for 28 days.

Table 5-1: The list of concrete specimen.

| **Name** | **w/c** | **Aggregate** | **Cement paste volume (%)** | **Aggregate volume (%)** | | |
|---|---|---|---|---|---|---|
| | | | | Total = | Coarse + | fine |
| Concr 0.30 Grnt | 0.30 | Granite | 30 | 70 | 42 | 28 |
| Concr 0.30 Lmst | 0.30 | Limestone | 30 | 70 | 42 | 28 |
| Concr 0.30 Grnt&Lmst | 0.30 | Granite+Limestone[a] | 30 | 70 | 42 (21+21) | 28 |
| Concr 0.48 Grnt | 0.48 | Granite | 30 | 70 | 42 | 28 |
| Concr 0.48 Lmst | 0.48 | Limestone | 30 | 70 | 42 | 28 |
| Concr 0.48 Grnt&Lmst | 0.48 | Granite+Limestone[a] | 30 | 70 | 42 (21+21) | 28 |
| Concr 0.30 Grnt/40[b] | 0.30 | Granite | 60 | 40 | 24 | 16 |
| Concr 0.30 Grnt/55 [b] | 0.30 | Granite | 45 | 55 | 33 | 22 |
| Concr 0.30 Grnt* [b] | 0.30 | Granite | 30 | 70 | 42 | 28 |

1% superplasticizer (by mass of cement) was used in specimens with w/c = 0.30.

The proportions of coarse and fine aggregates were 60% and 40% of total aggregate volume and the volume ratio of coarse to fine aggregate is 1.5 for all specimens.

[a] The proportions of granite and limestone aggregates were 50% of coarse aggregate volume.

[b] The specimens were cured for 28 days.

## 5.4. Materials: simultaneous attack of the leachate and mechanical abrasion

### 5.4.1. Cement paste

The abrasion resistance of mature cement pastes of varying w/c ratios were tested after exposure to the synthetic leachate solution for up to 120 days. Table 5-2 provides the list of the cement paste materials tested. All cement paste materials were cast in 2 × 2 × 24 inch prismatic PVC molds and were seal-cured for one year. They were then cut into 2 × 2 × 2 inch cubes before the start of exposure to the synthetic leachate solution or water. In addition to the effect of w/c, the effect of fiber and commercial chemical surface hardeners were studied. The fibers were

the synthetic polymeric fibers complying with ASTM C1116 type III and composed 1% of the cement paste volume. The chemical surface hardener was a typically commercially available product consisting mainly of lithium silicate. It was applied to the entire surface of the specimens with a brush and dried for more than 24 hours before an abrasion test or exposure to acidic solution (following recommendations of the manufacturer).

All cement paste specimens were fully submerged in the synthetic leachate solution inside a high-density polyethylene container. The overall volume ratio of the specimens to acidic solution was 0.95. The pH of the acidic solution was monitored daily and the solution was replaced with new solution when the pH rose to 10. This resulted in daily solution replacement for the first 8 days and every two days afterward. After 30, 60 and 120 days exposure, a set of specimens (three replicates) were taken out of the acidic solution and tested for abrasion resistance.

Table 5-2: The list of cement paste specimens.

| Name | w/c | Additive/treatment |
|---|---|---|
| Paste 0.30 | 0.30 | - |
| Paste 0.42 | 0.42 | - |
| Paste 0.48 | 0.48 | - |
| Paste 0.30F | 0.30 | Polymeric Fiber |
| Paste 0.42F | 0.42 | Polymeric Fiber |
| Paste 0.30SH | 0.30 | Surface hardener |
| Paste 0.42SH | 0.42 | Surface hardener |

### 5.4.2. Concrete

The list of concrete materials tested is shown in Table 5-3. Granite and limestone aggregates with 1/2 inch maximum aggregate size were used. In all concrete mixtures, the total volumetric aggregate content was 70% (28% fine aggregate and 42% coarse aggregate by volume). In mixtures containing silica fume, polymeric fibers, and latex emulsion, commercially available products were used. In concrete mixtures with w/c = 0.30, 1% (by mass of cement) commercially available superplasticizer was used. Two concrete mixtures containing latex were produced; in the case of Concr 0.30 Grnt-Ltx, the water content of the latex emulsion was accounted for so that the final w/c remained constant at 0.30, and in the case of Concr 0.47 Grnt-Ltx the water content of the latex emulsion was not corrected resulting in a w/c of 0.47, while ratio of cement to mixing water was 0.30 (two common practices in the field). All concrete mixtures were cast in 2 × 2 × 24 inch prismatic PVC molds and were seal-cured for six months to reduce the effect of their maturity [13]. They were then cut into 2 × 2 × 2 inch cubes before the start of exposure to the synthetic leachate solution.

All concrete specimens were fully submerged in the synthetic leachate solution inside a high density a high density polyethylene container. The overall volume ratio of the specimens to acidic solution was 0.95. The pH of the acidic solution was monitored daily and the solution was replaced with new solution when the pH rose to 10. This resulted in daily solution replacement for the first 7 days, every two days until day 43, every three days until day 73, and every four days afterward. After 30, 60, 120, and 180 days exposure, a set of specimens (three replicates) were taken out of the acidic solution and tested for abrasion resistance.

Table 5-3: The list of concrete materials.

| Name | w/c | Coarse aggregate | Reinforcement or admixture |
|---|---|---|---|
| Concr 0.30 Grnt | 0.30 | Granite | |
| Concr 0.30 Lmst | 0.30 | Limestone | |
| Concr 0.30 Grnt&Lmst | 0.30 | Granite+Limestone[a] | |
| Concr 0.30 Grnt-SF | 0.30 | Granite | Silica fume (5% of cement by W.) |
| Concr 0.30 Grnt-Fbr | 0.30 | Granite | Polymeric fiber (1.5% of cement by V.) |
| Concr 0.30 Grnt-Ltx | 0.30 | Granite | Latex (15% of cement by W.) |
| Concr 0.47 Grnt-Ltx | 0.47 | Granite | Latex (15% of cement by W.) |
| Concr 0.48 Grnt | 0.48 | Granite | |
| Concr 0.48 Lmst | 0.48 | Limestone | |
| Concr 0.48 Grnt&Lmst | 0.48 | Granite+Limestone[a] | |
| Mortar | 0.32[b] | - | |

1\% superplasticizer (by mass of cement) was used in mixtures with w/c=0.30.

[a] The proportions of granite and limestone aggregates were 50\% of the total aggregate by volume.

[b] The w/c=0.32 was used due to workability.

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# Appendix A: Survey questions

## Design of Waste Transfer Station Concrete Overlays against Premature Deterioration

**Project Overview:**

The premature deterioration of concrete overlays in waste transfer stations is a major concern for the owners and operators of these facilities. Overlay replacement in these facilities has significant economic impacts including direct costs, operational delays, and planning hurdles. Unfortunately, the contributing factors to the deterioration of concrete overlays in transfer stations and the mechanisms involved are not well understood.

**Objectives:**

The objectives of this survey are to (i) identify the design related and operational/performance factors that potentially contribute to the deterioration of concrete overlays in waste transfer stations, (ii) identify the level of contribution of each factor to the rate of deterioration, and (iii) gain an understanding of owner and operator expectations.

**GENERAL**

1. **Where is your waste transfer station located (5-digit Zip code)?**

2. **When was your facility constructed (YYYY)?**

3. **How long (in years) did each of the tipping floors last? Please provide the service duration for each floor if available.**
   **(If you do not know the answer, please leave the text entry empty)**
   First floor: _____years
   Second floor: _____ years
   Third floor: _____ years
   Fourth floor: _____ years

4. **Does the current in-service tipping floor show any sign of distress?**
   a. Yes
   b. Yes

5. **Does the current in-service tipping floor show any sign of distress such as random cracking, spalling, delamination, excessive aberration, aberration of the paste, or any other durability concerns? If Yes, please select as many that apply.**
   a. Random cracking: Uncontrolled discrete cracking with random shapes
   b. Map cracking: Extensive uncontrolled cracking that visually resembles a "map"
   c. Spalling: The separation of concrete pieces from the floor resulting in potholes; concrete pieces are generally a few inches in each dimension; generally observed at joints and adjacent to cracks.
   d. Delamination: The loss of adhesion between the tipping floor and the substrate; generally results in water accumulation underneath the tipping floor and manifests itself with water splashing when loader drives over the delaminated surface; can be detected by a "hollow sound" in hammer tapping.
   e. Cement paste aberration: The loss of cement paste in between the aggregates resulting in a rough surface with visible aggregates
   f. Excessive uniform floor aberration: The loss of slab thickness due to aberration.
   g. Others: _____

6. **What type is your waste transfer station?**
   a. Open top
   b. Surge pit
   c. Other:_____

7. **What is the total area of the tipping floor of your waste transfer station (in $ft^2$)?**
   Approximate total area: _____ $ft^2$

8. **What is the <u>permitted capacity</u> of your waste transfer station (tons/day)? And what is the <u>daily average</u> amount of waste received by your waste transfer station**
   Permitted Capacity:_____(tons/day)
   Daily average amount:_____(tons/day)

9. **How many hours per week is the tipping floor at your waste transfer station utilized (the average working hours per week)?**
   a. Less than 40 hours
   b. 40-60 hours
   c. 60-80 hours
   d. 80-100 hours
   e. 100-168 hours

10. **What type of vehicles are used for waste delivery?**
    (If **'I don't know'** is selected, please leave the other boxes **unchecked**)
    a. Dump truck
    b. Roll-off truck
    c. Residential collection truck
    d. Pickup truck
    e. Other:_____
    f. I don’t know

11. **What is the approximate percentage of waste delivered by each of the methods below?**
    (The methods come from the selection of Q.11)

**MAINTENANCE**

1. **How often is the tipping floor washed?**
   a. Daily
   b. Weekly
   c. Monthly
   d. Never

2. **Do you use any kind of detergent for washing the tipping floor?**
   a. Yes
   b. No

3. **In addition to washing the floor, do you scrape or wipe the floor clean (for example, using a mattress)?**
   a. Yes
   b. No

4. **Do you use any kind of chemical surface hardener to harden the tipping floor?**
   a. Yes
   b. No

**OPERATOR TRAINING LEVEL**

1. **Has the loader operator(s) received any specific training with regards to the amount of allowable load exerted by the loader bucket on the tipping floor?**
   a. Yes
   b. No

2. **How long have each of the loader operators been working at your waste transfer station?**
   a. Operator 1:_____years
   b. Operator 2:_____years
   c. Operator 3:_____years
   d. Operator 4:_____years
   e. Operator 5:_____years
   f. Operator 6:_____years
   g. Operator 7:_____years
   h. Operator 8:_____years
   i. Operator 9:_____years
   j. Operator 10:_____years

**WASTE TYPE**

1. **Does your facility receive recyclable waste on a separate section of the tipping floor?**
   a. Yes
   b. No

2. **What kind of recyclable waste does your facility receive?**
   (If **'I don't know'** is selected, please leave the other boxes **unchecked**)
   a. Glass
   b. Plastic
   c. Metal
   d. Others:___
   e. I don't know

3. **What is the approximate composition of the recyclable waste delivered?**
   (The kinds of recyclable waste come from the selection of Q.2)

4. **Where does the received waste come from?**
   (If **'I don't know'** is selected, please leave the other boxes **unchecked**)
   a. Residential
   b. Commercial
   c. Restaurant
   d. Industrial
   e. Construction and demolition debris
   f. Other
   g. I don't know

5. **What is the approximate percentage of the categories selected?**
   (The categories come from the selection of Q.4)

**EQUIPMENT**

1. **What type of loader(s) is used on the tipping floor?**
   Make:_____
   Model:_____

2. **Is the loader customized? If Yes, please indicate any available information about the customization.**
   **ex) CAT 272D XHP : Air-tires are replaced with solid rubber tires.**
   a. Yes
      Customization:_____
   b. No

3. **How often are the loader tires replaced?**
   a. within 15 days
   b. within 30 days
   c. within 60 days
   d. within 90 days
   e. over 90 days

4. **How often are the loader bucket arms replaced?**
   a. within a year
   b. within 2~3 years
   c. within 4~5 years
   d. over 5 years
   e. never

5. **Are there any protective materials installed at the cutting edge of the loader bucket?**
   a. Rubber
   b. Hard plastic
   c. Used tire
   d. Other:_____
   e. No (i.e., metal contact)

6. **How often is the protective material at the edge of the loader bucket replaced?**
   a. within 15 days
   b. within 30 days
   c. within 60 days
   d. within 90 days
   e. over 90 days

**DESIGN**

1. **Does the tipping floor consist of a single solid layer of concrete or it is layered?**
   a. A single solid section
   b. Layered
   c. Do not know

2. **(A single solid section) What does the floor rest on?**
   a. Gravel
   b. Sand soil
   c. Supported by other structures
   d. Other:_____

3. **If layered, what does the top overlay rests on?**
   e. Structural floor
   f. Soil
   g. Stone or gravel
   h. Plastic sheeting
   i. Other:_____
   j. Do not know

4. **If layered, what is the top overlay made of?**
   a. Normal concrete
   b. High strength concrete
   c. Fiber reinforced concrete
   d. Cement + emery aggregate
   e. Cement + iron aggregate
   f. Polyurethane + iron aggregate
   g. Epoxy + normal aggregate
   h. Epoxy + emery aggregate
   i. Other:_____
   j. Do not know

5. **If layered, how thick is the top overlay?**
   a. Less than 3 in.
   b. 3~6 in.
   c. 6~9 in.
   d. 10~13 in.
   e. 14~17 in.
   f. 18~21 in.
   g. More than 21 in.
   h. Do not know

6. **What is the <u>design service life</u> of the current tipping floor?**
   a. < 5 year
   b. 5~9 years
   c. 10~14 years
   d. 15~19 years
   e. 20 or over 20 years
   f. Permanent
   g. Do not know

7. **What is the <u>actual anticipated service life</u> of the current tipping floor (how long do you think this floor will last)?**
   a. < 1 year
   b. 1~2 years
   c. 3~4 years
   d. 5~6 years
   e. 7~8 years
   f. 9~10 years
   g. 11~14 years
   h. 15~20 years
   i. Do not know

8. **How often do you have to repair the tipping floor? (e.g., fill the crack, patch the floor)**
   a. within 1 year
   b. every 1~2 years
   c. every 3~4 years
   d. every 5 and over 5 years
   e. Not regularly but when necessary

**REPAIR**

1. **Has the current tipping floor been repaired?**
   a. Yes
   b. No

2. **How long can you shut down your facility for the repair of the tipping floor (days)?**
   Days:_____

3. **When repaired, is the floor repaired only at the distressed areas or is the entire floor repaired?**
   a. Only cracks are repaired
   b. Distress areas are repaired
   c. The entire floor is repaired
   d. The entire floor is resurfaced

4. **What percentage of the tipping floor remains operational during the repair or resurfacing operations?**
   a. The entire floor is shut down
   b. Percentage of the tipping floor remaining operational during the repair:_____%

5. **How long does it take to repair the cracks on the tipping floor (days)?**

   Days:_____

6. **How long does it take to resurface the tipping floor (days)?**

   Days:_____

7. **How do you know the tipping floor requires repair?**
   a. Visual distress
   b. Ride quality of the floor
   c. Some measurements
   d. Do not know

**ADDITIONAL INFORMATION**

1. **Are you willing to provide us with any of the information bellow?**
   a. Drawing of the facility
   b. Drawing of the tipping floor
   c. Concrete mixture design of the tipping floor

2. **If selected, can we visit your facility?**
   a. Yes
   b. No

3. **Can you provide us the name and contact information for someone knowledgeable of the design and operation of the transfer station? Please provide the information below.**

4. **Please provide any other comment and recommendations for this study. For your information we have provided the objectives of the research and the survey.**

   The **objectives of this research** are (i) to identify the contributing factors to the premature deterioration of concrete overlays in transfer stations, and (ii) to establish a structural design methodology for the concrete overlay based on the observed degradation mechanism and operational conditions.
   The **objectives of this survey** are to (i) identify the design related and operational/performance factors that potentially contribute to the deterioration of concrete overlays in waste transfer stations, (ii) identify the level of contribution of each factor to the rate of deterioration, and (iii) gain an understanding of the expectations of owners and operators.

## Appendix B: Survey Results

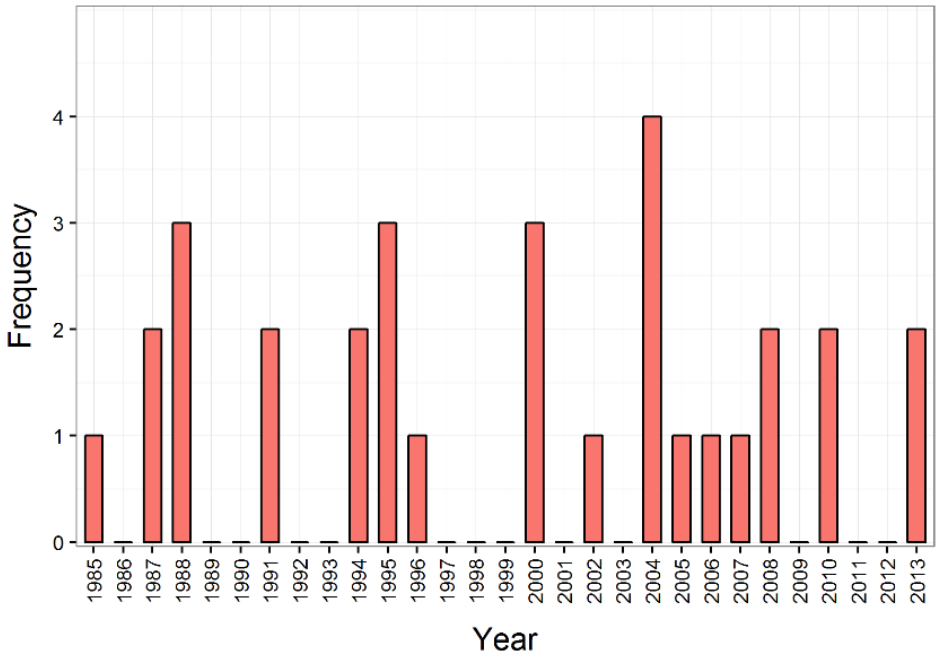
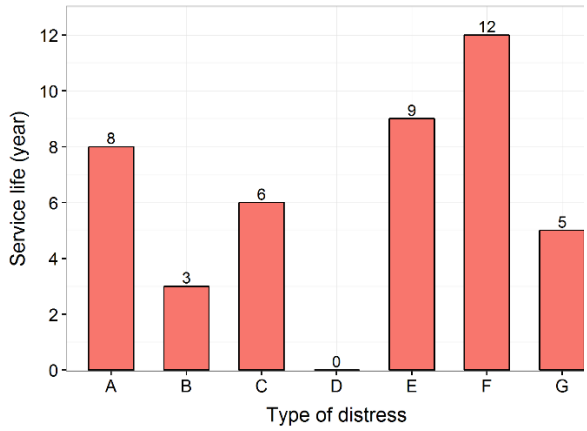



Figure B1: Histogram of the year participating facilities were constructed.




**A. Random cracking**: Uncontrolled discrete cracking with random shapes.

**B. Map cracking**: Extensive uncontrolled cracking that visually resembles a "map".

**C. Spalling**: The separation of concrete pieces from the floor resulting in potholes; generally observed at joints and adjacent to cracks.

**D. Delamination**: The loss of adhesion between the tipping floor and the substrate;

**E. Cement paste aberration**: The loss of cement paste in between the aggregates resulting in a rough surface with visible aggregates.

**F. Excessive uniform floor aberration**: The loss of slab thickness due to aberration.

**G. Other**

Figure B2: Reported distress signs on the facility floor. The most observed types of floor distress was E and F which are attributed to abrasion by vehicles.

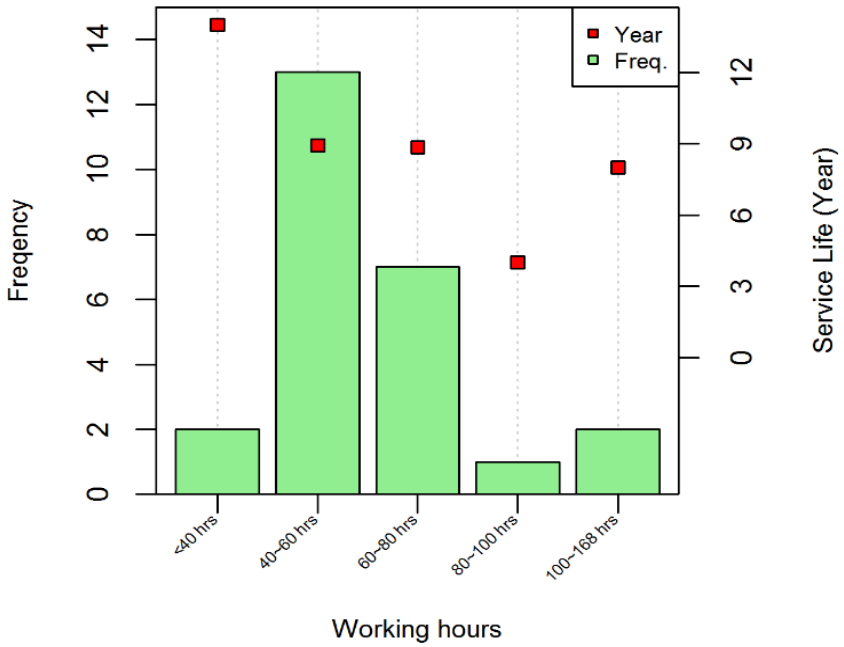



Figure B3: The relationship between operating hours and service life. Most of facilities operate 40~80 hours per week. The service life of the tipping floor depends on duration of operation per days (hours/day).

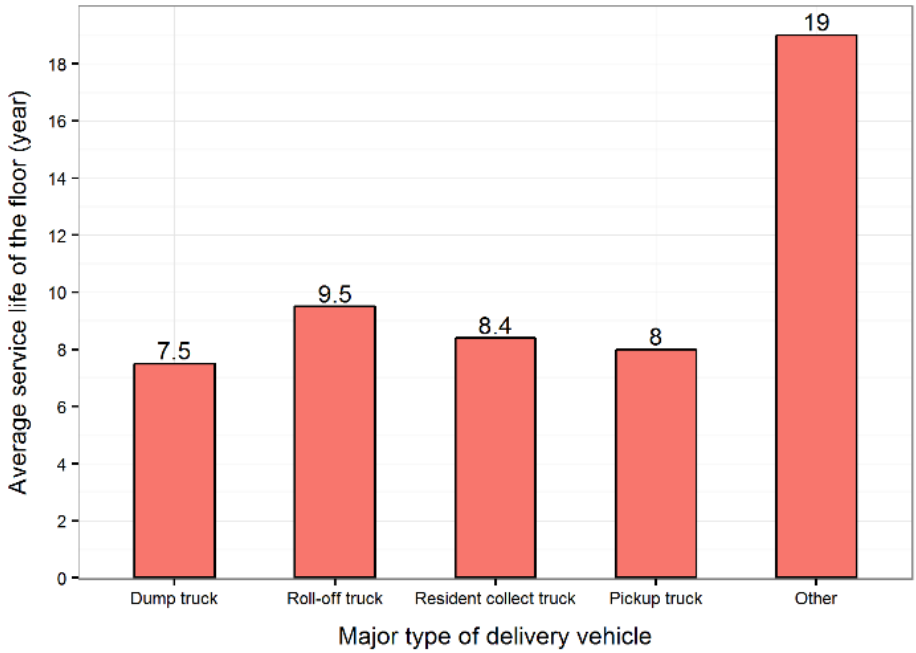
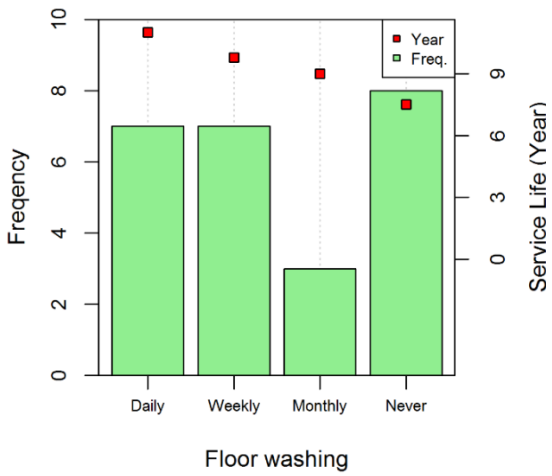
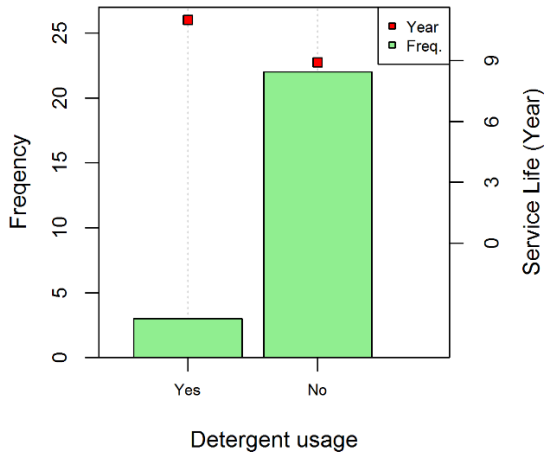


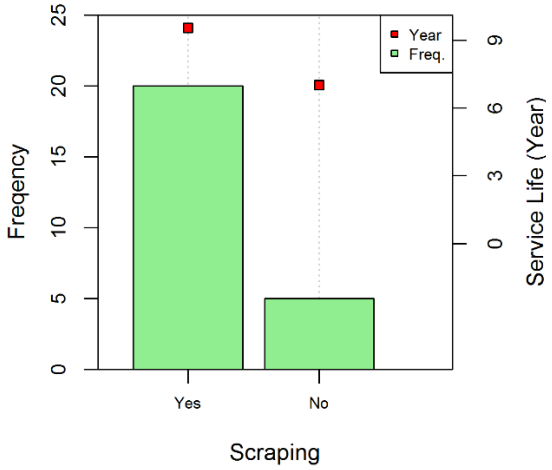

Figure B4: The relationships between waste delivery vehicle type and the average floor service life. It seems that the type of waste delivery vehicles does not affect the floor service life.



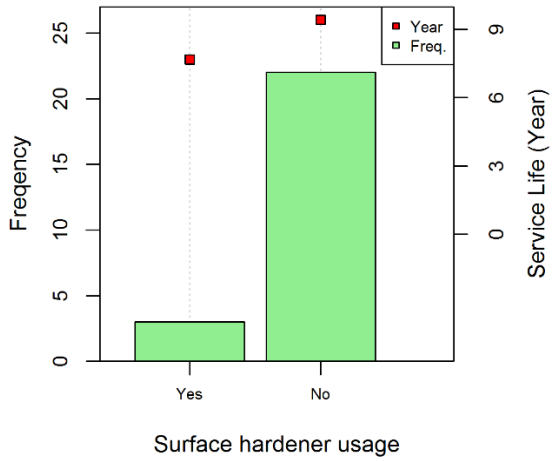

(a) Floor washing frequency




(b) Detergent usage




(c) Floor scraping




(d) Surface hardener usage

Figure B5: Floor maintenance results: (a) washing the floor significantly increases the the floor service life, (b) and (c) the use of detergent or scraping may be beneficial to prevent acid attack by waste leachate, and (d) Surface hardener decreases abrasion resistance of concrete floor subjected to waste leachate.

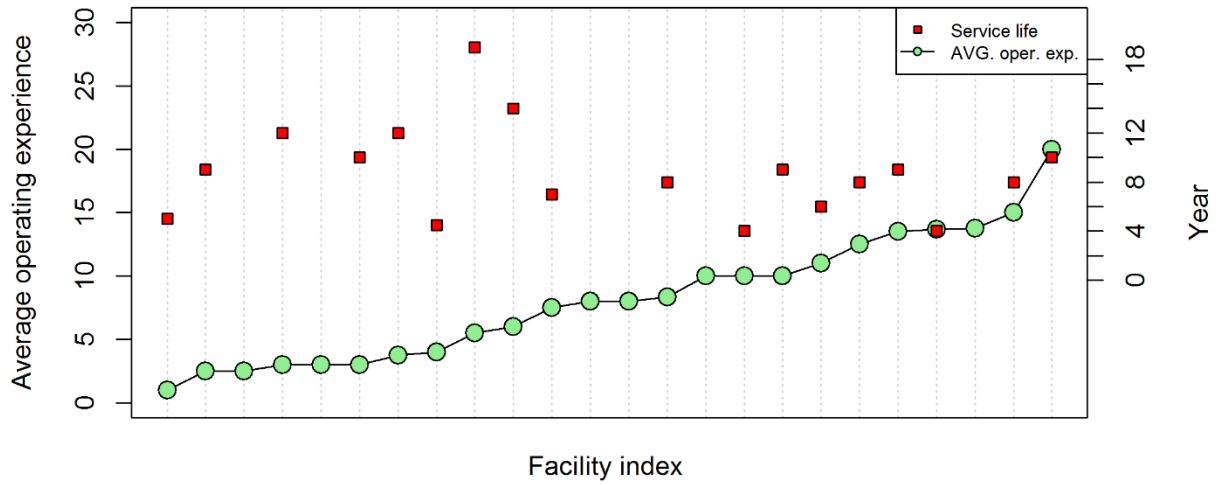



Figure B6: The relationship between the loader operator's work experience and the floor service life. The operator's work experience level does not correlate with the floor service life.

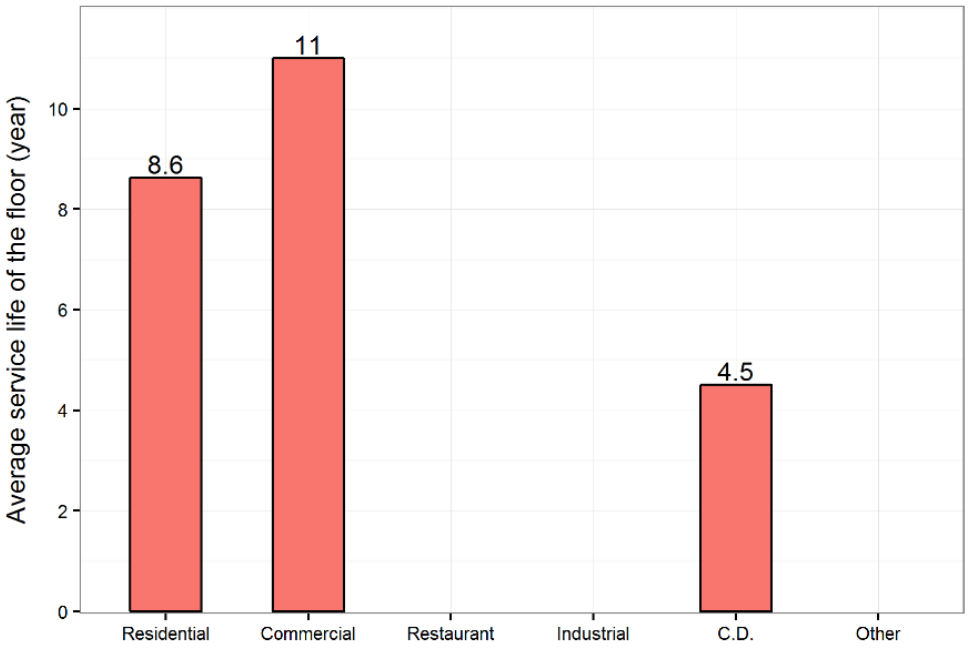
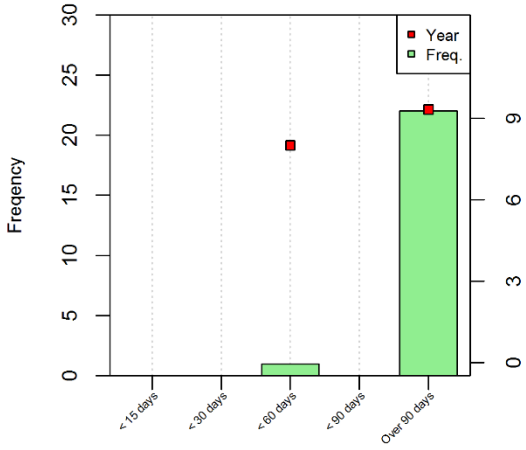
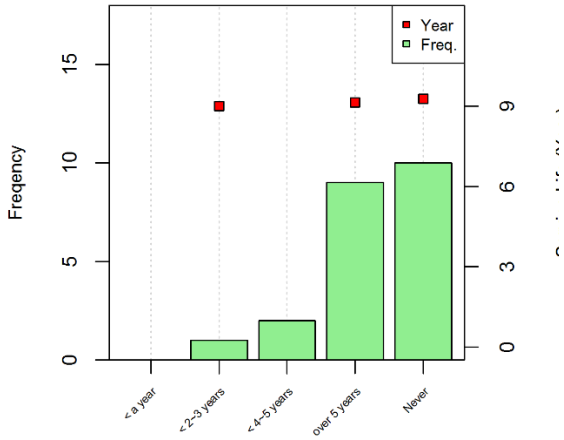


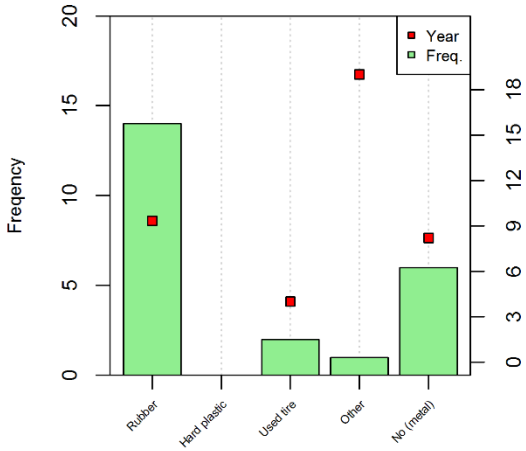

Figure B7: The relationship between waste origin and the floor service life. The tipping floor of the facilities that mainly serve residential areas has a shorter floor service life. The reason may be that the waste from residents contains more organic acids from food than commercials waste. The shortest reported floor service life was for a facility that receives construction and demolition debris (C.D.) due to severe mechanical abrasion. The lack of results for “Restaurant”, “Industrial”, and “Other” indicates that no facility has them as a major customer.



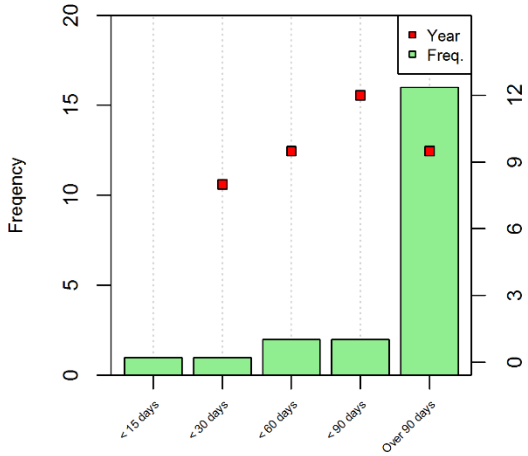

(a) Tire replacement




(b) Arm replacement




(c) Type of bucket protection




(d) Bucket protection replacement

Figure B8: Equipment working on facilities and the floor service life: (a) and (b) The replacements of loader tire and arm do not have a correlation with the floor service life, (c) Most loaders use rubber type bucket protection, (d) The bucket replacement period is highly correlated to the floor service life. Waste transfer stations with a longer service life of tipping floor, less frequently replace loader bucket protection rubber. This may be due the fact that the service life of the floor and the bucket protection rubber are both influenced by the amount of force excreted by the loader (mechanical abrasion).

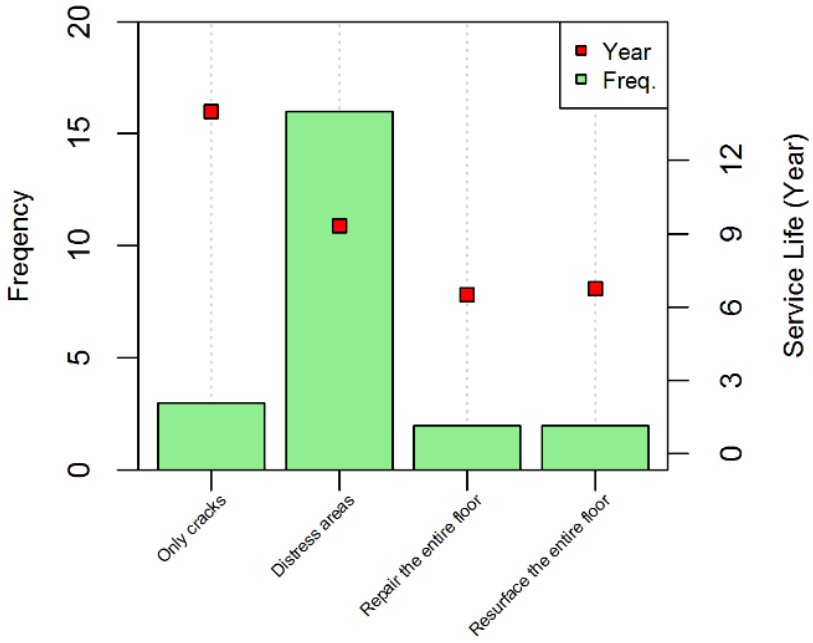



Figure B9: Most of facilities prefer to repair the distress area only rather than to repair or resurface the entire floor. It is assumed that the facilities need to remain in operation during the repair and construction time is critical for facility management. Therefore, facilities prefer local repair.

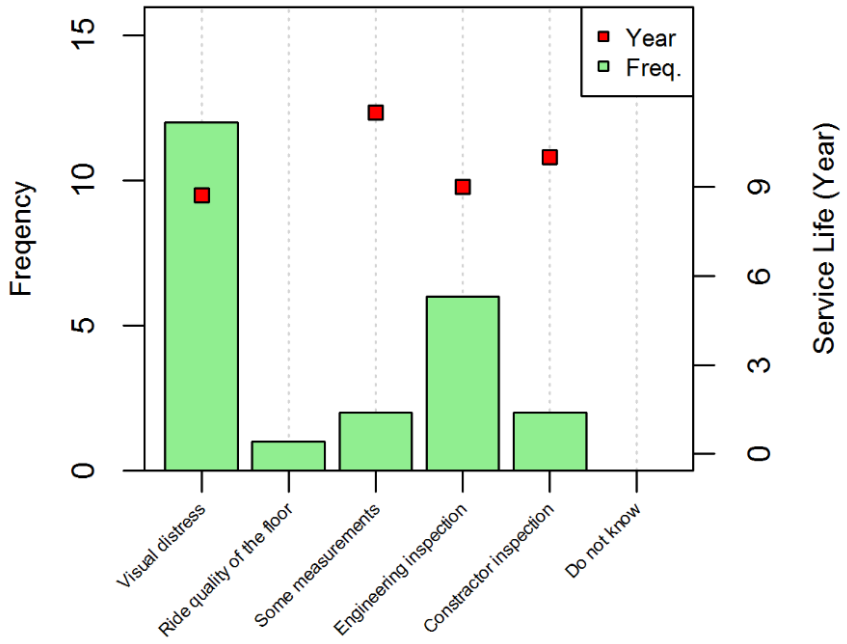
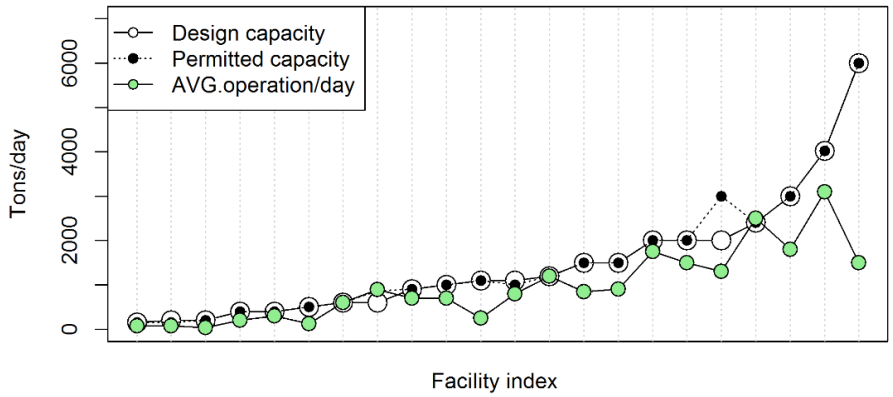
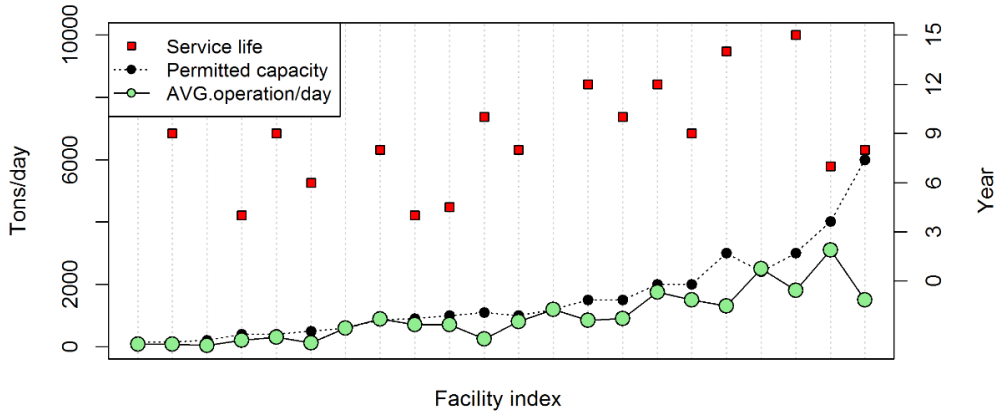


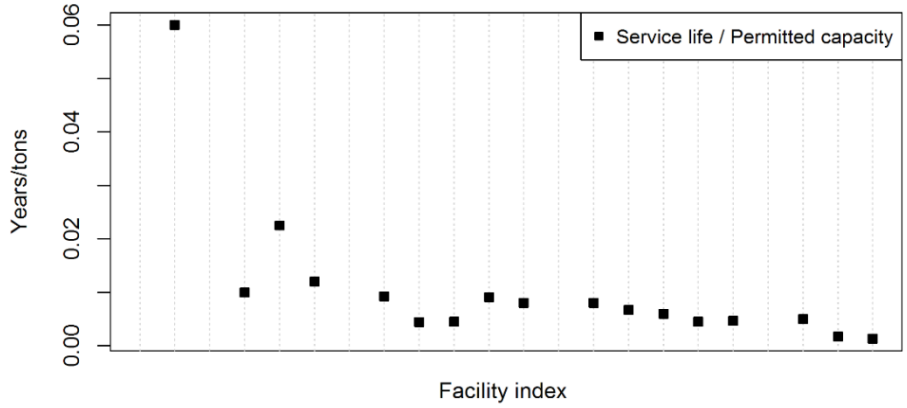

Figure B10: The “time-for-repair” is selected based on visual observations rather than engineering estimates or quantitative measurements.




(a)




(b)




(c)

Figure B 11: (a) Comparison of the design capacity, permitted capacity, and operational capacity for the waste transfer stations. The permitted capacity and the design capacity are almost equal; (b) service life of the waste transfer station with different capacities; (c) normalized service life to the permitted capacity.