

Utilization of local raw materials and mine waste to manufacture cement in Northwest Territories, Canada

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Abstract

Currently, all the cement consumed in Northwest Territories (NWT), Canada, is imported from other provinces (e.g., Alberta) by long-distance (~ 1,800 km) truck freight. Transporting cement over long distances not only raises its cost, but also results in a higher carbon footprint. Locally producing cement is a potential low-carbon and economic solution for the local industry. However, it is unknown if the local raw materials are suitable for cement manufacturing; and there is a lack of a critical raw material—Iron ore—for cement manufacturing. Instead of iron ore, there are iron-rich tailings from a local rare earth element (REE) mine. Towards low-carbon and circular economy, this study explored the use of local raw materials (i.e., limestone, clay, and gypsum) and mine waste (REE tailings) to manufacture cement in the NWT and successfully produced the first bag of cement in the history of the NWT. The results showed that concrete samples made with NWT cement achieved comparable strength of commercial OPC-based concrete. An emission estimation suggested that locally producing cement in the NWT has the potential to reduce 3.0% - 61.7% of CO₂ emissions when compared with importing cement from other provinces.

Keywords: Mine Waste, Cement Manufacturing, Circular Economy, Cementitious Materials, UN SDG 11, UN SDG 12

1. Introduction

The mining industry is the largest contributor to the economy of Northwest Territories (NWT), Canada, accounting for about 25% of the territorial GDP [1]. During mining operation, cement-based materials (e.g., concrete, shotcrete, and backfill) are essential parts of rock support and infrastructure construction [2]. Given the versatility of cement-based materials, a vast amount of cement is consumed annually by the mining and construction industries in the Northwest Territories (NWT) of Canada (Huang et al., 2019, Arachchilage et al., 2023, Olive, 2003). Currently, all the cement consumed in the NWT is imported from other provinces (e.g., Alberta) and transported over long distances (~ 1,800 km) by freight trucks. The long-distance

26 transportation not only bumps up the price (over 50%) of cement but also increases the carbon footprint (about 0.2 tonne
27 CO₂/tonne cement), ultimately affecting the profit and sustainability of the mining and construction industries of the NWT.
28 Locally manufacturing cement with their geological materials is a potential solution for reducing the carbon footprint and costs
29 related to cement consumption in the NWT.

30 Generally, Portland cement is manufactured with limestone, clay, iron ore, and gypsum through a complex process, including
31 raw materials quarrying, crushing, proportioning, grinding, homogenizing, calcination, and cement clinker grinding (del
32 Strother, 2019). Recently, the NWT Geological Survey identified sources of limestone, clay, and gypsum in the NWT. However,
33 iron ore resource was not found yet in the NWT. Iron ore is an essential raw material for Portland cement manufacturing; it
34 provides an iron source to form one of the main mineral phases—brownmillerite (Ectors et al., 2013, del Strother, 2019). In
35 addition, iron ore affects the fuel consumption and quality of cement products. The lack of iron content in the raw meal will
36 decrease the liquid phase content during burning, reduce the coating tendency, then increase the difficulty in burning and
37 clinkerization, ultimately affecting the fuel consumption and quality of cement products (Kurdowski, 2014, Chatterjee, 1983).

38 Due to the above-mentioned significant roles of iron ore, it is important to find alternative iron sources for locally manufacturing
39 cement in the NWT. Instead of iron ore, there are some iron-rich tailings from a rare earth element (REE) mine in the NWT,
40 which might be a suitable raw material for cement manufacturing. From the literature (Vilaplana et al., 2015, Young and Yang,
41 2019, Alp et al., 2009, Luo et al., 2016, Sarmiento et al., 2019), there are successful cases of using solid waste as a raw material
42 for cement manufacturing. For example, Vilaplana et al. (Vilaplana et al., 2015) utilized steel industrial waste—ladle furnace
43 slag and mill sludge—as raw materials and successfully prepared a 52.5 R Portland cement product that met the requirement of
44 British Standard EN 197-1 (Standardization, 2011). In their study, replacing limestone and iron ore with ladle furnace slag and
45 mill sludge not only reduced natural raw material consumption, but also mitigated CO₂ emissions from cement manufacturing
46 due to the lower limestone content in the raw meal. Alp et al. (Alp et al., 2009) reported an industrial-scale trial of using pyrite
47 cinders—a solid waste product from sulphuric acid plants—as an iron source for Portland cement manufacturing; the results
48 showed that the cement product prepared with pyrite cinders had similar performance as CEM I type cement. In addition, Young
49 and Yang (Young and Yang, 2019) added high-magnesium and low-silicon iron ore tailings into raw meals to prepare Portland
50 cement; they found that the iron ore tailings were suitable for cement manufacturing. Yet the content of iron ore tailings was
51 advised to be less than 20%; otherwise, a significant reduction (e.g., 24%) would be observed in the unconfined compressive
52 strength (UCS) of samples (Young and Yang, 2019).

53 The previous successful cases (Vilaplana et al., 2015, Young and Yang, 2019, Alp et al., 2009, Luo et al., 2016, Sarmiento et
54 al., 2019) of utilizing solid waste for cement manufacturing inspired the authors to explore the possibility of using local raw
55 materials and mine waste to locally produce cement in the NWT. Using these raw materials and mine waste to locally produce
56 cement can contribute significantly to the economy and environment of NWT. First, locally producing cement can avoid the
57 extra costs and emissions from long-distance truck freight, reducing the costs and emissions related to cement consumption in
58 the NWT. Second, it can provide a sustainable solution for disposing of the tailings of the rare earth element mine, reduce the
59 occupation of landmass for tailing disposal, and mitigate the environmental impact of these tailings. In addition, it is able to
60 increase the value of local geological materials (e.g., limestone, clay, and gypsum) and mine waste, diversify the local economy,
61 and create more job opportunities. Despite these potential benefits, it remains unknown if these raw materials and mine waste
62 are suitable for cement production. There is a significant need to explore the suitability of these local raw materials and mine
63 waste for cement production.

64 The main aim of this study is to investigate whether it is possible to utilize the local raw materials and mine waste to produce
65 cement in the NWT. For this objective, the raw materials and mine waste from the NWT will be utilized to prepare cement on
66 a laboratory scale; then experiments will be conducted to evaluate the performance (including mineral compositions, loss on
67 ignition, setting time, workability, hydration reaction, volume stability, and compressive strength) of lab-prepared cement with
68 the raw materials and mine waste from the NWT. In addition, the performance of lab-prepared NWT cement will be compared
69 with commercial Ordinary Portland Cement (OPC) and Canadian Standard Specifications for cementitious materials.

70 **2. Methodology**

71 ***2.1. Cement manufacturing in a laboratory***

72 Fig. 1 shows the overview of the methodology of this study, and Fig. 2 presents the workflow of preparing cement in a laboratory.
73 The detailed procedures are described as follows. First, the raw materials (limestone, clay, gypsum, and REE tailings) from
74 NWT were crushed, dried at 105 °C, and pulverized with a ball mill. Then the chemical compositions of the raw materials were
75 characterized for the raw material proportion. The oxide compositions of the raw materials and mine waste were determined
76 with thermogravimetric analysis (TGA) and Scanning Electron Microscopy Energy Dispersive Spectroscopy (SEM-EDS). The
77 results are presented as shown in Table 1.

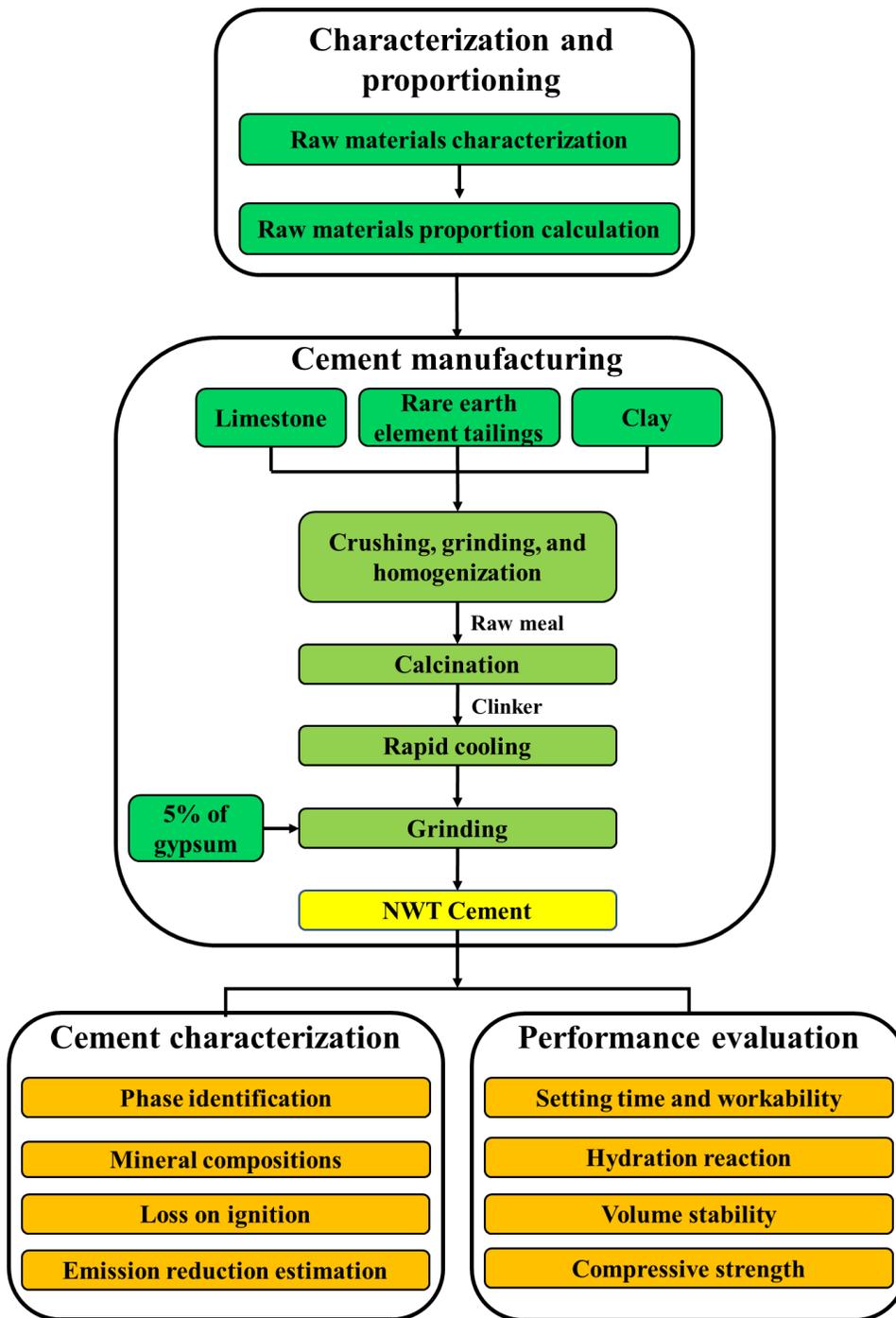


Fig. 1 Overview of the methodology.

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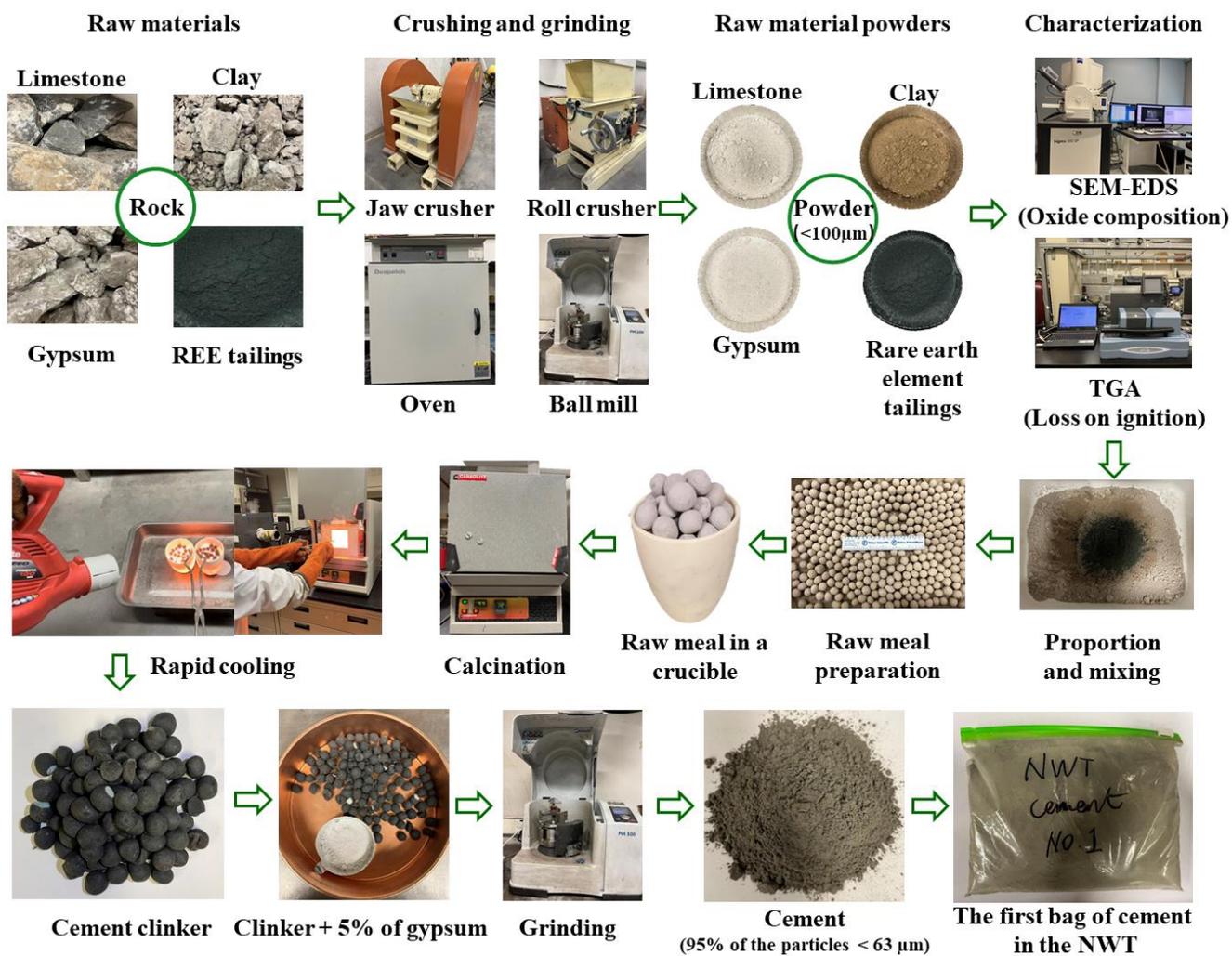


Fig. 2 Workflow of manufacturing cement in a laboratory

Table 1 Chemical compositions of raw materials (in mass %)

Raw materials	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	K ₂ O	Na ₂ O	SO ₃	TiO ₂	LOI
Limestone	53.19	2.75	0.83	0.17	0.77	0.06	0	0	0	42.23
Clay	1.40	61.67	16.57	5.79	2.36	3.67	1.62	0.73	0.76	5.43
REE tailings	11.47	41.27	6.96	30.23	4.53	3.30	0.96	0.33	0.38	0.08
Gypsum	36.19	1.64	0.51	0.19	0.70	0.13	0	44.85	0.02	15.76

Based on their oxide compositions, the proportions of each raw material in the raw meal were calculated to ensure a good quality of the lab-prepared cement clinker. To achieve this, we adjusted the proportions of each raw material to make the lime

87 saturation factor (LSF), alumina ratio (AR), and silica ratio (SR) at reasonable ranges. The equations used to calculate these
 88 parameters and the suggested ranges by previous researchers are shown in Table 2 (del Strother, 2019, Vilaplana et al., 2015).
 89 In this study, the raw material proportion calculation was performed with an embedded solver in Microsoft Excel. The calculated
 90 proportion of raw materials and the calculated LSF, AR, and SR values are listed in Table 3. As shown in Table 3, limestone,
 91 clay, and REE tailings should be added at 79.5%, 15.5%, and 5%, respectively. At such a proportion, the LSF, SR and AR were
 92 0.965, 2.256, and 1.405, respectively. In other words, all of the parameters (LSF, SR, and AR) were located in a suggested
 93 range (del Strother, 2019, Vilaplana et al., 2015).

94

95 Table 2 Equations for parameter calculation and their suggested ranges (del Strother, 2019, Vilaplana et al., 2015).

Parameters	Equations	Suggested range
Lime saturation factor (LSF)	$LSF = \frac{\%CaO}{2.8 * \%SiO_2 + 1.2 * \%Al_2O_3 + 0.65 * \%Fe_2O_3}$	0.94-0.98
Silica ratio (SR)	$SR = \frac{\%SiO_2}{\%Al_2O_3 + \%Fe_2O_3}$	2.0-2.6
Alumina ratio (AR)	$AR = \frac{\%Al_2O_3}{\%Fe_2O_3}$	1.2-1.6

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98 Table 3 Proportion of raw materials and calculated LSF, SR, and AR.

Raw materials	Calculated proportion	Calculated LSF, SR, and AR
Limestone	79.5%	LSF=0.965
Clay	15.5%	SR=2.256
REE tailings	5%	AR=1.405

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100 After calculation, the pulverized raw materials were weighed, mixed, and homogenized. Water (25% of the raw materials) was
 101 added to mixed raw materials to enable the raw materials bind together. Then the raw materials were kneaded into small spheres

102 to ensure even heating during calcination. The raw meal spheres were oven-dried, and then placed in a crucible and calcinated
 103 in a muffle furnace. The temperature in the muffle furnace will be increased from 20 °C to 1450 °C at 16 °C/min and maintained
 104 at 1450 °C for 30 minutes (Clavier et al., 2021). Each time, two crucibles of the raw meals (~350 g × 2) were calcined. Following
 105 calcination, crucibles with clinkers were cooled down to ~50 °C within several minutes to mitigate the transformation from
 106 alite to belite. Finally, the cement clinker with 5% gypsum addition was milled down to cement powders (~95% < 60 μm as per
 107 previous study (Vilaplana et al., 2015)) using a ball mill, leading to the final lab-prepared product. This lab-prepared cement
 108 powder was named as NWT cement.

109 **2.2. Cement characterization and performance evaluation**

110 After cement manufacturing, cement characterization and performance evaluation were conducted to examine if they meet the
 111 standard specification for Portland cement (CSA Group, 2018). A Mastersizer 3000 laser particle size diffraction analyzer was
 112 employed to measure the particle size distribution of the NWT cement. During the tests, cement particles were dispersed in
 113 isopropanol. TGA and X-ray diffraction (XRD) were conducted to determine the loss on ignition (LOI) and identify the crystal
 114 phases of the NWT cement. During the TGA test, 1.2 ± 0.05 g of cement samples were heated from room temperature (20 °C)
 115 to 980 °C at a heating rate 10 °C/min under oxygen atmosphere with a Leco TGA 701. XRD test was carried out with Co K α
 116 radiation using an Ultima IV X-ray diffractometer in a 2 θ -range of 5° - 70° at a step size of 0.02° and a scan speed of 2.0°/min.
 117 In addition, Bogue's equations (del Strother, 2019) were used to calculate the potential mineral compositions of the NWT
 118 cement.

$$C_3S = 4.071 \times CaO - 7.602 \times SiO_2 - 6.719 \times Fe_2O_3 - 1.430 \times Fe_2O_3 \quad (1)$$

$$C_2S = -3.071 \times CaO + 8.602 \times SiO_2 + 5.068 \times Al_2O_3 + 1.079 \times Fe_2O_3 \quad (2)$$

$$C_3A = 2.650 \times Al_2O_3 - 1.692 \times Fe_2O_3 \quad (3)$$

$$C_4AF = 3.043 \times Fe_2O_3 \quad (4)$$

119 As for the performance of NWT cement, experiments were conducted to determine the setting time, workability, volume
 120 stability, and strength development of cement paste or concrete samples prepared with NWT cement. At the same time, cement
 121 paste and concrete samples prepared with commercial ordinary Portland cement (OPC) were also cast and tested for comparison.
 122 In this study, the setting time and workability of cement paste samples with a w/c ratio of 0.3 were determined with a Vicat
 123 Needle apparatus following the ASTM C191 standard (2013) and a flow table as per the ASTM C1437-15 standard (ASTM
 124 Interantional, 2015). Volume stability and UCS of concrete samples with a water-to-cement (w/c) ratio 0.45 and an aggregate-

125 to-cement ratio of 3.125 were measured. This mixture design was modified from ACI 506.5R-09 (American Concrete Institute,
126 2009), which is a standard for cement-based materials for underground rock support and is widely used to guide concrete design
127 for underground mines in North America. The volume stability of concrete samples was evaluated following ASTM C157
128 standard (ASTM international, 2017). The UCS of concrete samples were measured at 1 day, 7 days, and 28 days as per the
129 ASTM C39 standard (2018). In addition, cement paste samples with the same w/c ratio as the samples for UCS tests were
130 prepared for TGA test, which can help understand the hydration of cement and help explain the strength behavior. The hydration
131 of cement paste samples was stopped at 1 day, 7 days, and 28 days by immersing them in isopropanol and rinsing with diethyl
132 ether, and then the samples were oven-dried at 40 °C as per the procedure suggested in RILEM TC-238 recommendation
133 (Snellings et al., 2018).

134 **3. Results and discussion**

135 ***3.1. Unreacted cement characterization***

136 Fig. 3 depicts the particle size distributions of the NWT cement and commercial OPC. The $D_{50\%}$ and $D_{90\%}$ of the NWT cement
137 as 17.89 μm and 56.20 μm , respectively. This means that 50% of cement particles (in volume) had a size smaller than 17.89
138 μm ; 90% cement particles were smaller than 56.20 μm . The particle size of the lab-prepared NWT cement had similar particle
139 sizes with the lab-prepared cement by previous researchers (Vilaplana et al., 2015). In their study, 95.3% of cement had a
140 particle size smaller than 60 μm . The particle size of the NWT cement was obviously larger than commercial OPC, of which
141 the $D_{50\%}$ and $D_{90\%}$ were 11.40 μm and 31.42 μm , respectively. This is because cement grinding aid, widely used by cement
142 manufacturers, was not added during the grinding process. In future studies and manufacturing, it is recommended grinding aid
143 be added to help with the grinding process because it can reduce the energy consumption required for crushing cement particles
144 (Toprak et al., 2020, Engelsen, 2008). In addition, cement grinding aid can mitigate the re-agglomeration of cement particles
145 by reducing the van der Waals Force and increasing the electro-static repulsion force between cement particles (Toprak et al.,
146 2020, Engelsen, 2008). In these ways, grinding aid can help reduce cement particle size, grinding time, and energy consumption
147 during the grinding process.

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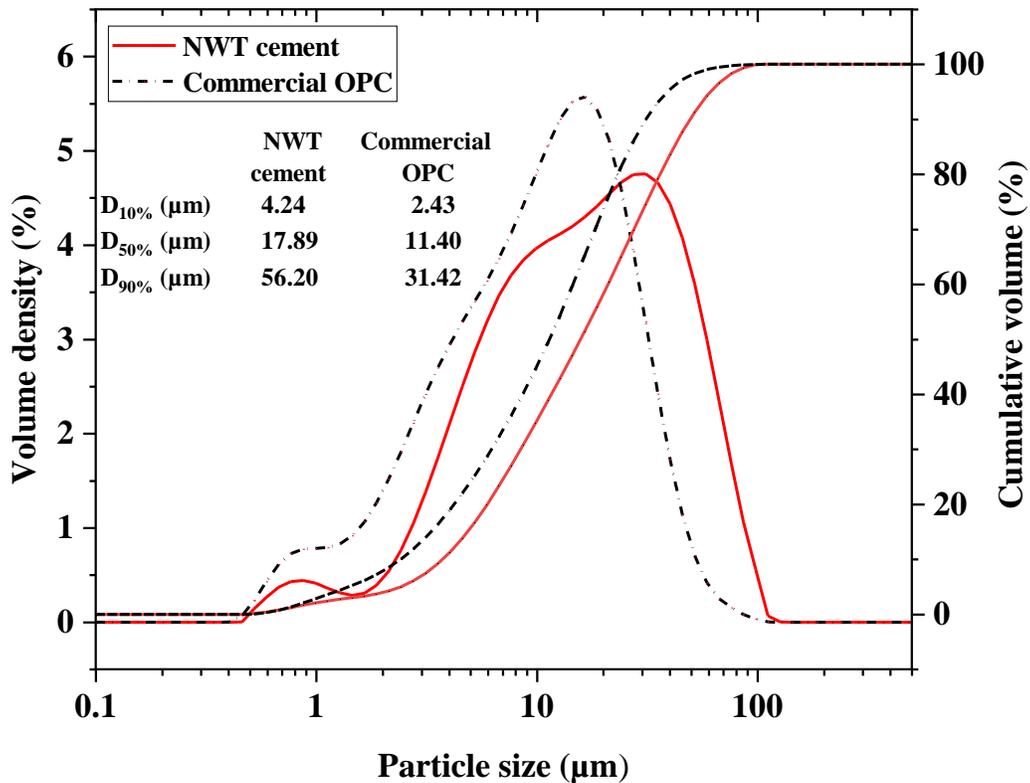


Fig. 3 Particle size distribution of cement samples

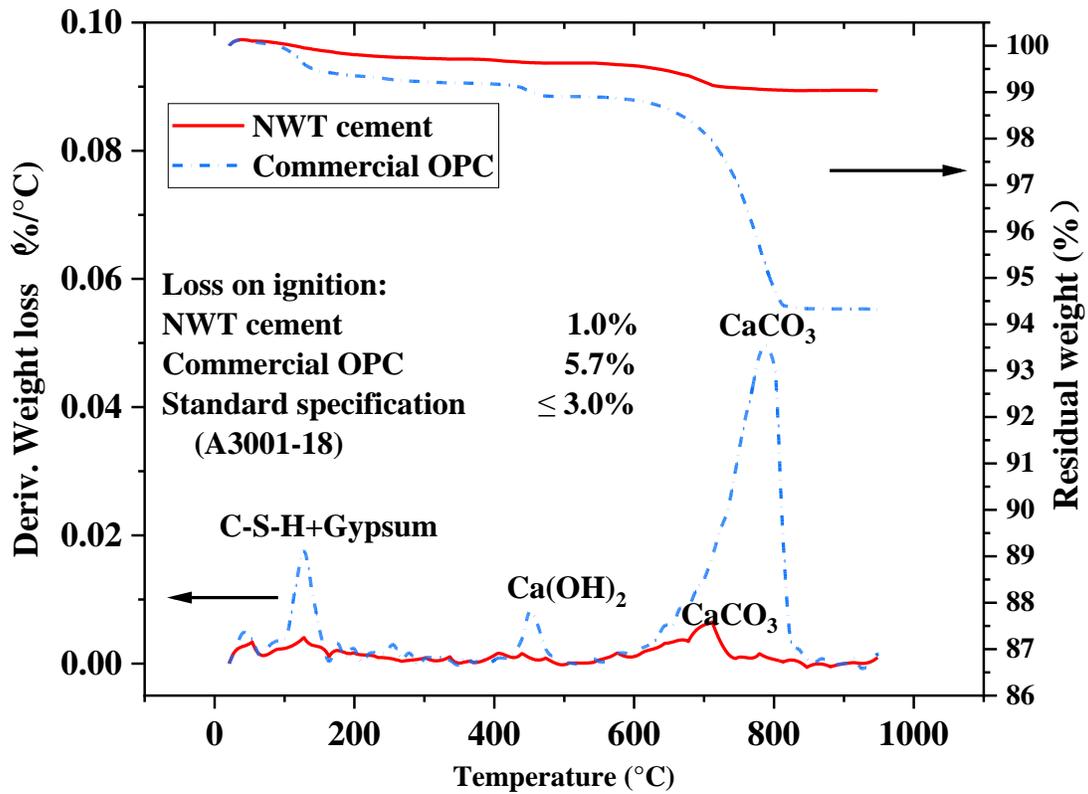
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151 As shown in Fig. 4, the TGA results of unreacted NWT cement and commercial OPC are plotted as residual weight and
 152 derivative weight loss. The LOI of the unreacted cement equals 100% minus the residual weight (in %) of cement sample at
 153 950 °C. The derivative weight loss can reflect what caused the LOI because different minerals decomposed at different
 154 temperature ranges.

155 The LOI of NWT cement was only 1.0%, which was much smaller than the maximum value (3.0%) for Type General Use (GU)
 156 cement specified in A 3001-18 standard (CSA Group, 2018). The LOI of NWT cement resulted from the dehydration of gypsum
 157 at ~100 °C to 170 °C, and the decomposition of calcium carbonate (CaCO₃) occurred at around 700 °C. This content of CaCO₃
 158 was account for 1.1% of total cement mass; the formation of CaCO₃ can be attribute to the carbonation reaction of cement with
 159 CO₂ in air during the rapid cooling process and the grinding process. The LOI (5.7%) of commercial OPC was higher than that
 160 of NWT cement. This higher LOI of commercial OPC could be attributed to two reasons. First, limestone was added as an
 161 ingredient in the commercial OPC, according to the data from its manufacturer. The decomposition of CaCO₃ in the limestone
 162 resulted in the LOI of commercial OPC. In addition, commercial OPC reacted with moisture in air to form hydration products,

163 such as calcium silicate hydrate (C-S-H) and calcium hydroxide (CH), during the packing, transporting, and storing processes.
 164 The decomposition of C-S-H and CH also caused the LOI of commercial OPC.



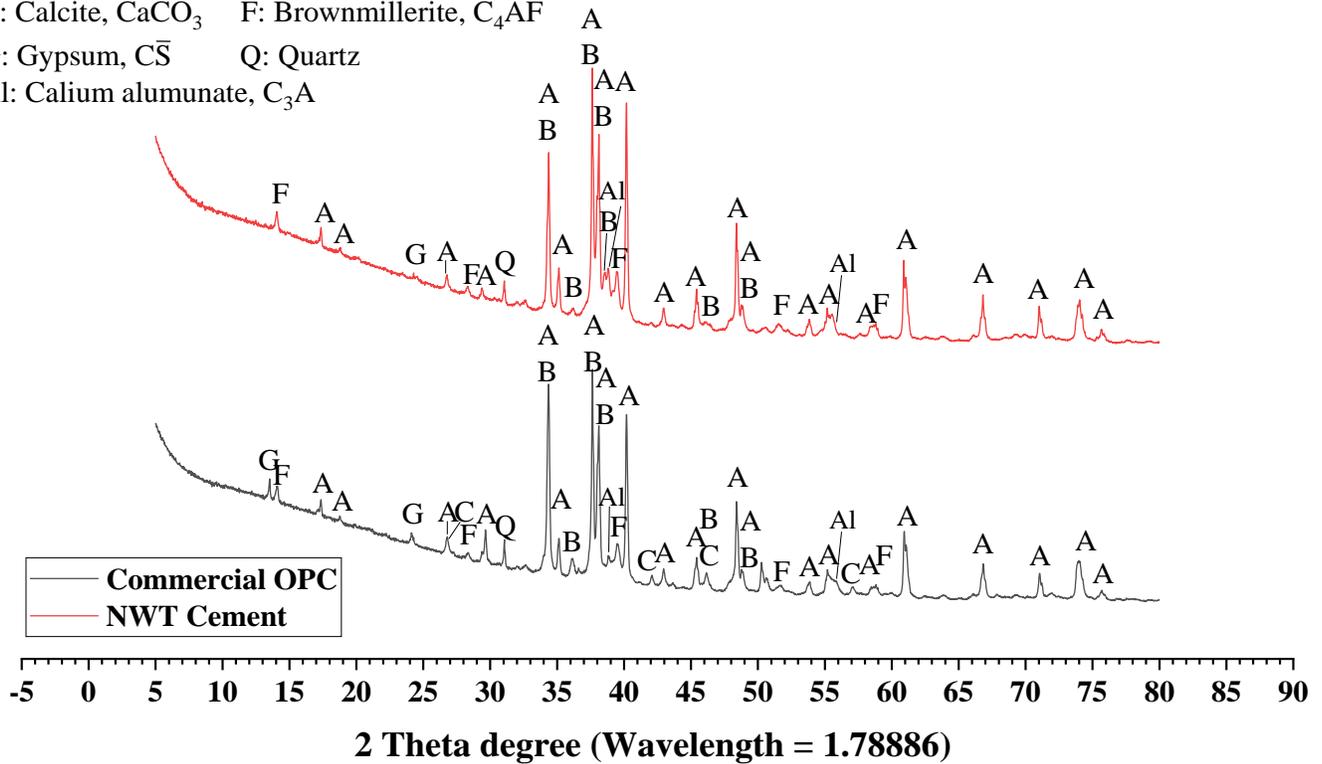
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Fig. 4 TGA results of unreacted cement

167 The mineral compositions of the unreacted cement are displayed in Fig. 5 and Table 4. Fig. 5 shows that mineral compositions
 168 in the NWT cement were alite, belite, calcium aluminate, brownmillerite, and gypsum, which were similar to those of
 169 commercial OPC. The difference between NWT cement and the commercial OPC was that more obvious peaks for calcite
 170 (CaCO₃) were observed in the XRD patterns of commercial OPC. This coincides with the TGA results that a higher signal
 171 accounting for the decomposition of CaCO₃ was found in the derivative weight loss curve of commercial OPC. In addition to
 172 XRD phase identification, Bogue's Equations were used to calculate the content of the main minerals in unreacted cement. As
 173 shown in Table 4, alite, belite, calcium aluminate, and brownmillerite content in the NWT cement was 62.8%, 10.8%, 7.6%,
 174 and 11.4%, respectively. The alite, belite, and brownmillerite content in the NWT cement was similar to that in commercial
 175 OPC, while the calcium aluminate content (7.6%) in the NWT cement was significantly higher than that (4.1%) of commercial
 176 OPC. Despite this difference, the calcium aluminate content (7.6%) in the NWT cement was in a normal range according to the

177 standard specification of mineral compositions of Portland cement listed in previous studies (Vilaplana et al., 2015).

A: Alite, C_3S B: Belite, C_2S
 C: Calcite, $CaCO_3$ F: Brownmillerite, C_4AF
 G: Gypsum, $CS\bar{2}$ Q: Quartz
 Al: Calium alumunate, C_3A



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Fig. 5 XRD patterns of unreacted cement

Table 4 Mineral compositions calculated with Bogue's Equations

Mineral composition	Alite (C_3S)	Belite (C_2S)	Calcium aluminate (C_3A)	Brownmillerite (C_4AF)
NWT cement	62.8	10.8	7.6	11.4
Commercial OPC*	62.7	9.9	4.1	10.8
Standard specification (Vilaplana et al., 2015)	40-80	0-30	7-15	4-15

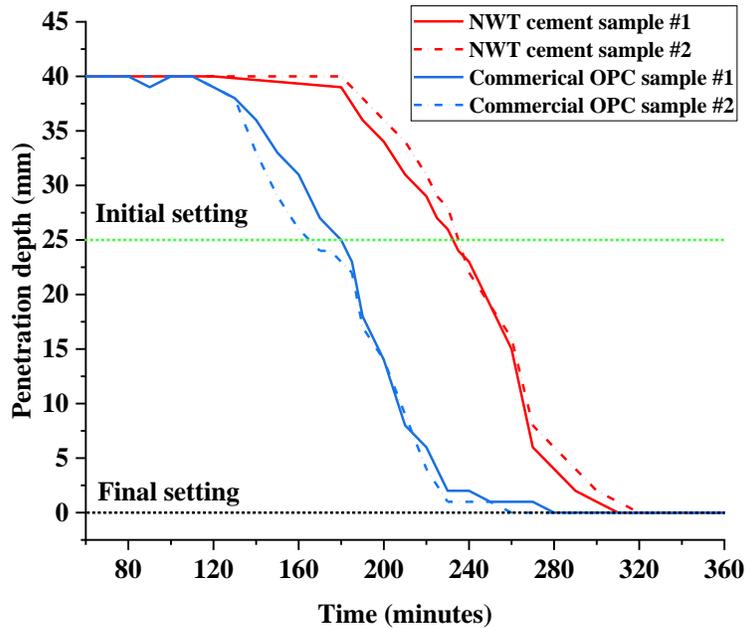
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*Provided by the commercial OPC manufacturer.

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3.2. Setting time

184 Setting time determines if cement-based materials have enough time to be mixed, transported, and placed in site properly before
 185 they lose their plasticity. In this study, the setting time cement paste samples was determined with a Vicat apparatus. During
 186 the tests, a steel rod with a needle was released and allowed to penetrate into cement paste samples. The penetration depths of
 187 needle on cement paste samples were recorded and plotted as shown in Fig. 6. According to the ASTM C191 standard (ASTM
 188 International, 2013), the initial setting time was defined as the time that the penetration depth is 25 mm, and the final setting
 189 time refers to the time when the needle cannot mark on the cement paste samples. Table 5 summarizes the initial and final
 190 setting time of cement paste samples based on the penetration depth plotted in Fig. 6. It shows that the initial setting time of
 191 NWT cement was 235 ± 5 minutes, which was ~ 60 minutes later than that of commercial OPC. The final setting time of NWT
 192 cement was 310 ± 5 minutes, 40 minutes slower than commercial OPC. Despite the slower setting, NWT cement still met the
 193 standard requirement (45-375 minutes) for initial setting time specified in the CSA A3001 Standard specification (CSA Group,
 194 2018).



195
 196 Fig. 6 Setting of cement pastes tested with a Vicat Needle apparatus

197 Table 5 Initial and final setting times of cement pastes

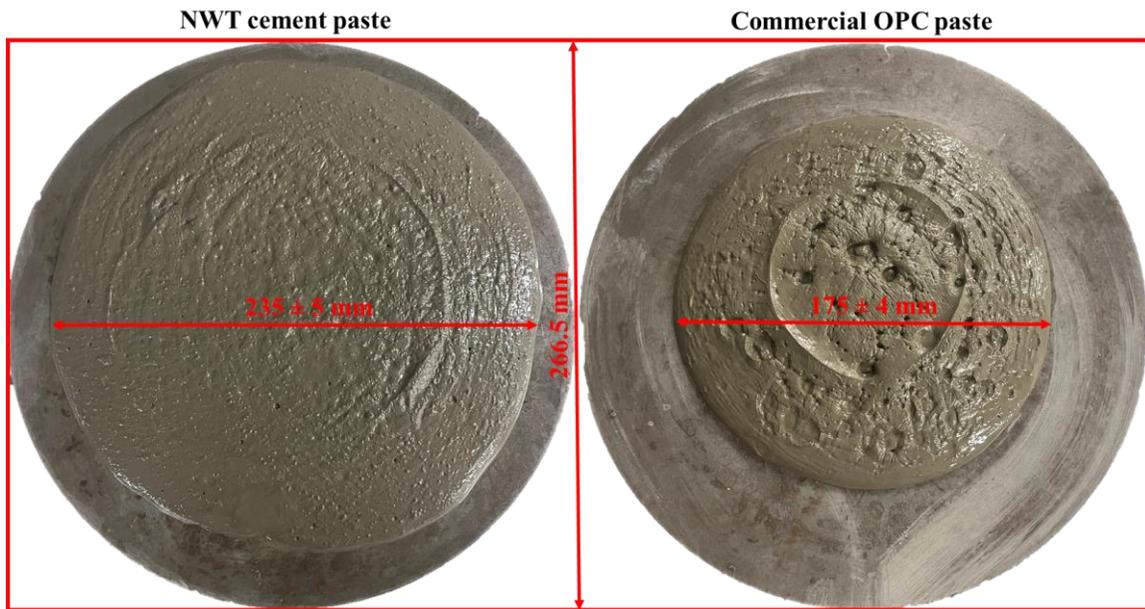
	Initial setting time (minutes)	Final setting time (minutes)
NWT cement	235 ± 5	310 ± 5

Commercial OPC	175±10	270±10
CSA A3001 Standard specification (CSA Group, 2018)	45-375	-
(Minimum-maximum)		

198

199 **3.3. Workability**

200 Workability describes how easily cement-based materials can be mixed, placed, and compacted. In this study, the workability
 201 of cement paste samples was determined with a flow table. During the test, cement paste samples were cast in a mold and placed
 202 on the top of the table. Then the mold was lifted, and the table was raised and dropped 25 times within 15 seconds. At last, the
 203 diameters of the cement paste samples were measured and depicted in Fig. 7. Fig. 7 shows that the flow diameter of NWT
 204 cement paste was 235±5 mm, which was ~60 mm larger than that of commercial OPC paste. The larger flow diameter indicated
 205 that NWT cement paste samples had better workability than commercial OPC paste samples.



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Fig. 7 Flow diameter of cement pastes

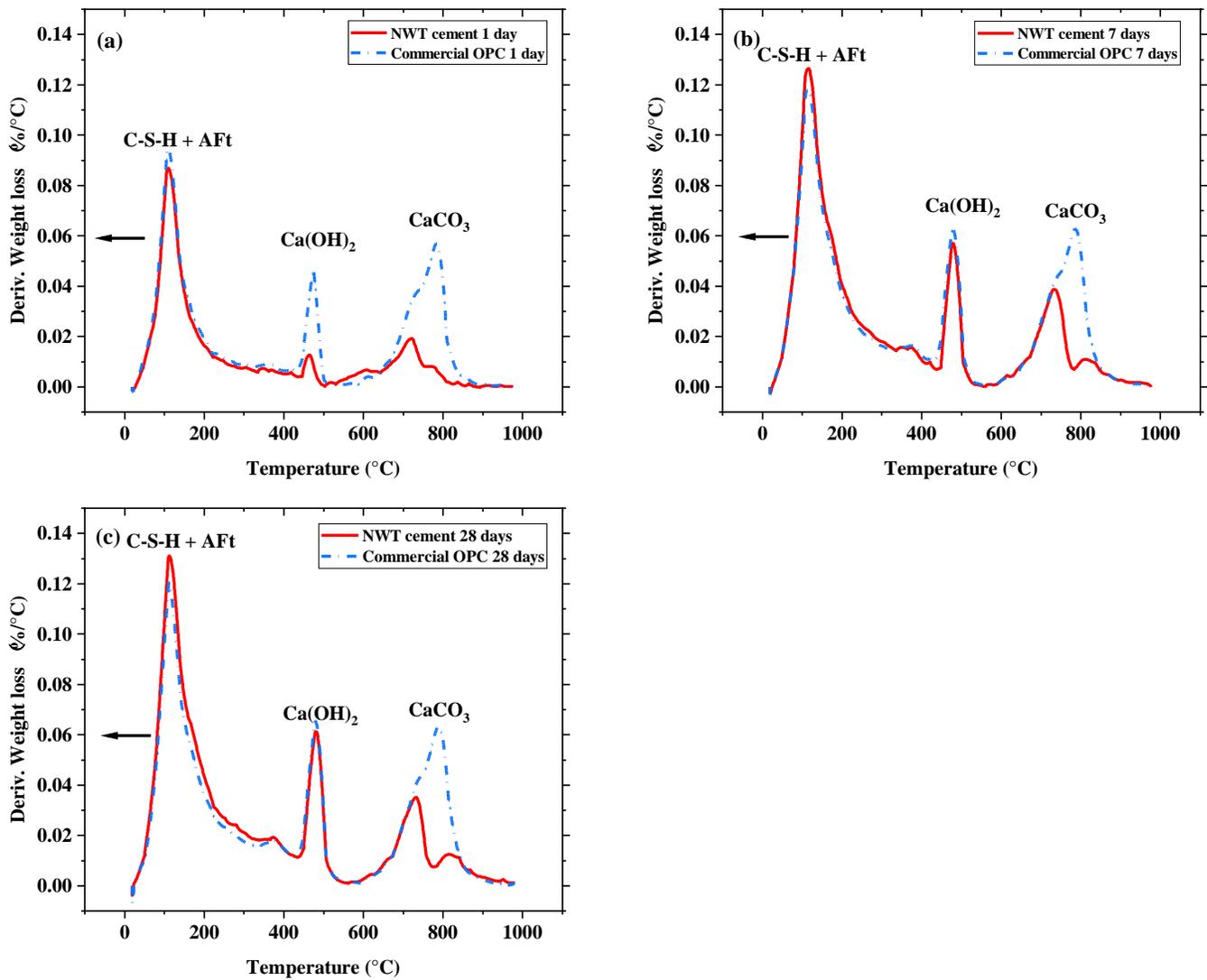
208 **3.4. Hydration reaction**

209 Hydration reaction is a chemical reaction between cement and water in cement-based materials. During hydration reaction,
 210 generated hydration products (e.g., calcium silicate hydrates (C-S-H), calcium hydroxide (CH), and ettringite (AFt)) will bond

211 all the ingredients, fill in the pores and voids in the cement-based materials, and gain strength over time. It is essential to
212 understand cement hydration reaction with time because it can help understand the performance of cement-based materials. In
213 this study, the hydration reaction of NWT cement was characterized with TGA tests at different ages (1 day, 7 days, and 28
214 days) and compared with that of commercial OPC.

215 As shown in Fig. 8, the results of TGA tests are depicted in the form of derivative weight loss. There are three peaks in each
216 curve, which indicate the decomposition of different hydration products. The first peak at approximately 110 °C was observed
217 due to the dehydration of C-S-H and AFt. The second peak at around 480 °C and the third peak at about 790 °C refer to the
218 decomposition of calcium hydroxide (Ca(OH)_2) and calcium carbonate (CaCO_3), respectively. C-S-H and Ca(OH)_2 are the
219 hydration products of alite or belite, while AFt was generated from the reaction between calcium aluminate, gypsum, and water.
220 CaCO_3 was detected for two reasons: (1) it existed in the unreacted NWT cement and commercial OPC as shown in the TGA
221 curves in Fig. 4; (2) the cement hydration products (C-S-H, AFt, and Ca(OH)_2) experienced carbonation (Huang et al., 2022).

222 The peak intensity reflects the amount of hydration products: a higher peak means a higher hydration degree. Fig. 8 (a) shows
223 that the peak intensity of C-S-H and Ca(OH)_2 of the NWT cement sample was lower than the commercial OPC sample. It
224 implies that less alite and belite in NWT cement paste reacted with water to form C-S-H and Ca(OH)_2 , indicating that the
225 hydration of NWT cement was slower than that of commercial OPC in the first 24 hours. This is because the particle size of
226 NWT cement was coarser than that of commercial OPC; cement reaction rate decreases with the decrease of cement fineness
227 (Liu et al., 2015, Hu et al., 2014). At 7 days, the C-S-H and Ca(OH)_2 peak intensity of NWT cement sample was similar to that
228 of commercial OPC sample, as shown in Fig. 8 (b). This suggests that the hydration of NWT cement sample accelerated from
229 1 day to 7 days, reached a similar hydration degree of commercial OPC sample at 7 days. At 28 days, the C-S-H and Ca(OH)_2
230 peak intensity of NWT cement sample and commercial OPC sample also similar. However, a considerable difference is still
231 observed in the CaCO_3 peak intensity. This is because there was more calcite in the unreacted commercial OPC as shown in
232 Fig. 4 and Fig. 5.



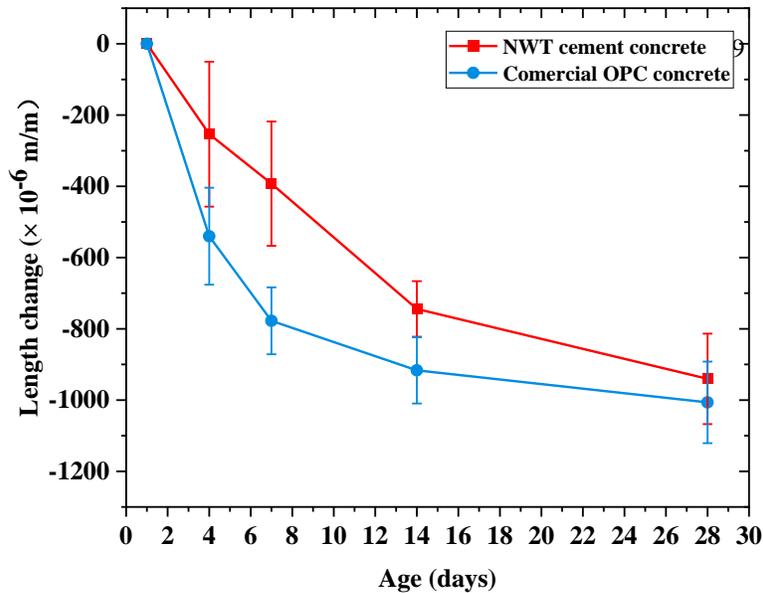
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 234 Fig. 8 TGA results of cement pastes after being cured for (a) 1 day; (b) 7 days; and (c) 28 days.

235 **3.5. Volume stability**

236 Cement-based materials tend to experience volume shrinkage over time for many reasons. For example, Portland cement reacts
 237 with water to form denser hydration products (e.g., C-S-H) with a smaller volume, which leads to chemical shrinkage; in
 238 addition, the gradual loss of moisture from the concrete samples over time results in drying shrinkage (Dhir et al., 2017). These
 239 shrinkages can cause cracks in the concrete structures and ultimately reduce their load-bearing capacity and durability (Zhan
 240 and He, 2019). Therefore, it is essential to evaluate the volume stability of cement-based materials.

241 In this study, the volume stability of NWT cement concrete was determined and compared with commercial OPC concrete, and
 242 the results were plotted in Fig. 9. It shows that shrinkage was observed on both NWT cement concrete and commercial

243 OPC concrete samples. At 4 days and 7 days, the shrinkage of NWT cement concrete was about half of that of commercial OPC
 244 cement concrete, indicating that NWT cement concrete had better volume stability at early ages. The smaller shrinkage could
 245 be partially attributed to the slower hydration reaction of NWT cement and a smaller chemical shrinkage at the early ages. At
 246 28 days, the shrinkage of NWT cement concrete was $\sim 940 \times 10^{-6}$ m/m, only 6.6% lower than that of commercial OPC concrete.
 247 The 28 days' data reflects that the NWT cement concrete has comparable volume stability as the commercial OPC concrete.
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250 Fig. 9 Volume stability of concrete samples

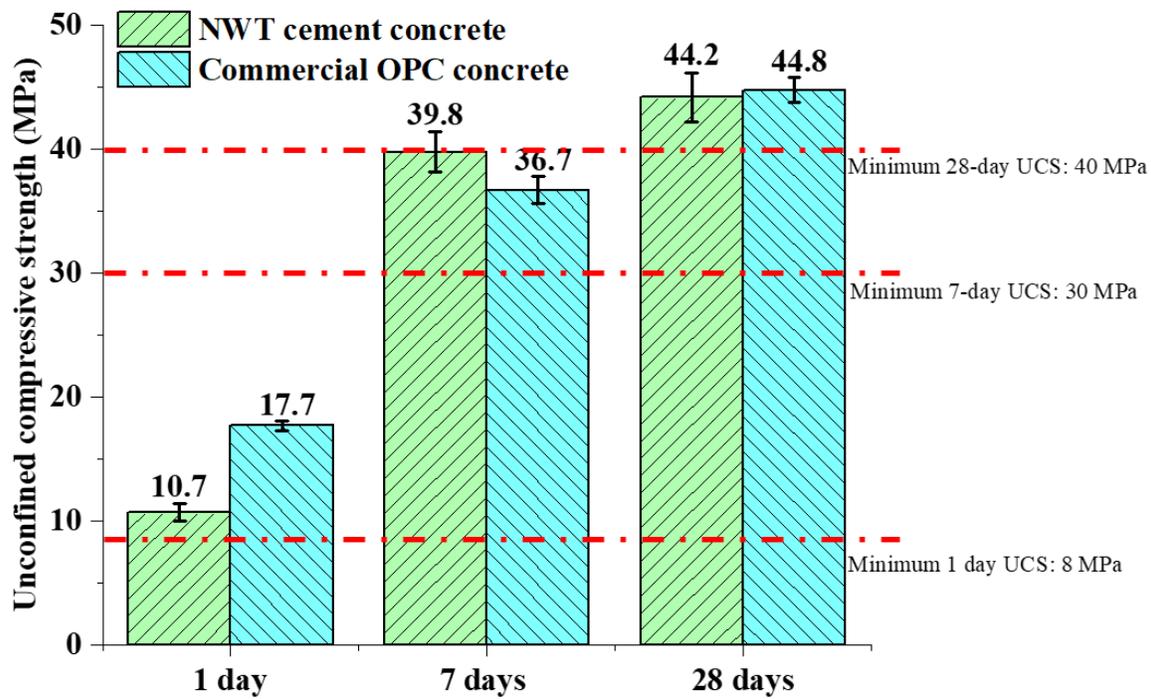
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252 3.6. Compressive strength

253 Compressive strength is one of the most important properties of concrete. In this study, UCS of concrete samples made with
 254 NWT cement was determined at 1 day, 7 days, and 28 days, then compared with the UCS of commercial OPC concrete samples.
 255 In addition, the UCS of NWT cement concrete at different ages was also compared with the minimum strength requirement
 256 specified in ACI 506.5R standard (American Concrete Institute, 2009)—a widely used standard guiding the concrete mixture
 257 design in underground rock support in North America.

258 As shown in Fig. 10, the NWT cement concrete gained a UCS of 10.7 MPa on the first day (24 hours), which was about 39.5%
 259 lower than that (17.7 MPa) of the commercial OPC concrete. The slower strength development of NWT cement concrete in the
 260 first day could be explained by the TGA results. On the first day, the hydration reaction of NWT cement was slower than
 261 commercial OPC, and fewer hydration products (e.g., C-S-H and $\text{Ca}(\text{OH})_2$) formed; as a result, the 1-day UCS of NWT cement

262 concrete was lower than that of commercial OPC concrete. Despite the slower strength development, the 1-day UCS of NWT
 263 cement concrete was still ~33.8% higher than the minimum 1-day UCS of concrete samples specified in ACI 506.5R standard
 264 (American Concrete Institute, 2009). From 1 day to 7 days, the strength development of NWT cement concrete accelerated, and
 265 the 7-day UCS of NWT cement concrete reached 39.8 MPa, ~8.4% higher than commercial OPC concrete. This UCS value was
 266 also ~32.7% higher than the minimum 7-day UCS specified in the ACI 506.5R standard (American Concrete Institute, 2009)
 267 and almost met the minimum 28-day UCS requirement. A high 7-day UCS of NWT cement concrete was observed because the
 268 hydration reaction of NWT cement was accelerated from 1 day to 7 days, and more hydration products (e.g., C-S-H and
 269 $\text{Ca}(\text{OH})_2$) were generated to form a denser and stronger structure. At 28 days, NWT cement concrete and commercial OPC
 270 concrete gained a comparable UCS; they are 10.5% and 12.0% higher than the minimum 28-day UCS specified in the standard.
 271 Based on the comparison with commercial OPC concrete and ACI 506.5R standard (American Concrete Institute, 2009) , it can
 272 be concluded that the strength development of NWT cement concrete met the strength requirement of cement-based materials
 273 for rock support in the mining industry.



274

275

276

277

Fig. 10 Compressive strength development of concrete samples

3.7. Emission reduction estimation

278 As to the potential environmental benefit, an emission reduction estimation was carried out to compare the emissions of
 279 manufacturing cement in the NWT and importing cement from other provinces. The potential emission reduction can be
 280 estimated with Eq. (1):

$$E_{Reduction} = 100\% \times \frac{(E_{Commercial\ OPC} + E_{transportation} - E_{NWT\ cement})}{(E_{Commercial\ OPC} + E_{transportation})} \quad (1)$$

281 In Eq. (1), $E_{Commercial\ OPC}$ is the emissions from commercial OPC manufacturing process, which were set as 0.838 tonne
 282 CO₂/tonne cement according to the Environmental Product Declaration of the commercial OPC manufacturer in 2022.
 283 $E_{NWT\ cement}$ is the potential emissions from NWT cement manufacturing in the NWT, which was assumed to be 0.5 - 0.9 tonne
 284 CO₂/tonne cement based on the data reported in previous studies (IEA, 2021, Sánchez et al., 2021, Valderrama et al., 2012).
 285 $E_{transportation}$ is the emissions generated during the transportation of commercial OPC from cement plant in other provinces
 286 to the NWT, which can be calculated with Eq. (2):

$$E_{transportation} = E_{Freight\ truck} \times D_{transportation} \times 10^{-3} \quad (2)$$

287 $E_{Freight\ truck}$ is the emission intensity from freight truck; it was set as 0.05 - 0.26 kg/tonne/km based on report by United States
 288 Environmental Protection Agency (United states Environmental Protection Agency, 2022) and Greenhouse Gas Protocol (Green
 289 House Gas Protocol, 2017). $D_{transportation}$ is the transportation distance when importing cement from other provinces. In this
 290 study, the transportation distance was assumed as 1800 km because the shortest transportation distance is about 1800 km from
 291 the cement plant in other provinces to Yellowknife (the Capital of NWT). The input parameters for the estimation are
 292 summarized and listed as shown in Table 6.

293

294 Table 6 Input parameters for emission reduction estimation.

	Importing from other provinces	Local production in NWT
Emissions from cement manufacturing (tonne CO ₂ /tonne cement)	0.838*	0.5 - 0.9 (IEA, 2021, Sánchez et al., 2021)
Transportation distance (km)	1800	-

0.05 - 0.26 (Green House Gas
Protocol, 2017, United states
Freight truck emissions (kg/tonne/km) -
Environmental Protection Agency,
2022)

295 * This number was obtained from the commercial OPC manufacturer’s Environmental Product Declaration released in 2022.
296 Fig. 11 depicts the results of potential emission reduction of producing cement in NWT compared with importing from other
297 provinces. As shown in Fig. 11, manufacturing cement locally in the NWT has the potential to reduce CO₂ emissions in a range
298 of ~3.0% to ~61.7% when the emission intensity of freight trucks was in a range of 0.05 - 0.26 kg/tonne/km and emissions from
299 NWT cement manufacturing were in a range of 0.5 - 0.9 tonne CO₂/tonne cement. The emission reduction highly depends on
300 the current emission intensity from freight trucks and the potential emissions to produce one tonne of cement in the NWT. The
301 higher the current emission intensity of freight trucks, locally manufacturing cement can help reduce more CO₂ emissions
302 related to long-distance cement transportation. Similarly, the lower the emissions from cement manufacturing in the NWT, the
303 more emission reduction will be achieved. For example, ~19.2% emission reduction can be achieved if the emissions from
304 NWT cement manufacturing are the same as that (0.838 tonne CO₂/tonne cement) reported by the commercial OPC
305 manufacturer when the emission intensity of freight truck is set as an average value (0.11 kg/tonne/km) according to
306 Environmental Defense Fund (Mathers et al., 2014). If the emissions from NWT cement manufacturing can be reduced to 0.8,
307 0.7, 0.6, 0.5 tonne CO₂/tonne cement, the emission reduction can be 22.8%, 32.4%, 42.1%, and 51.7%, respectively. For more
308 emission reductions, advanced technologies should be applied during cement manufacturing in the NWT, including but not
309 limited to reducing the clinker-to-cement ratio by replacing clinker with different additives, carbon capture and storage, and
310 using cleaner fuel and electricity (Ali et al., 2011, Sharma et al., 2021).

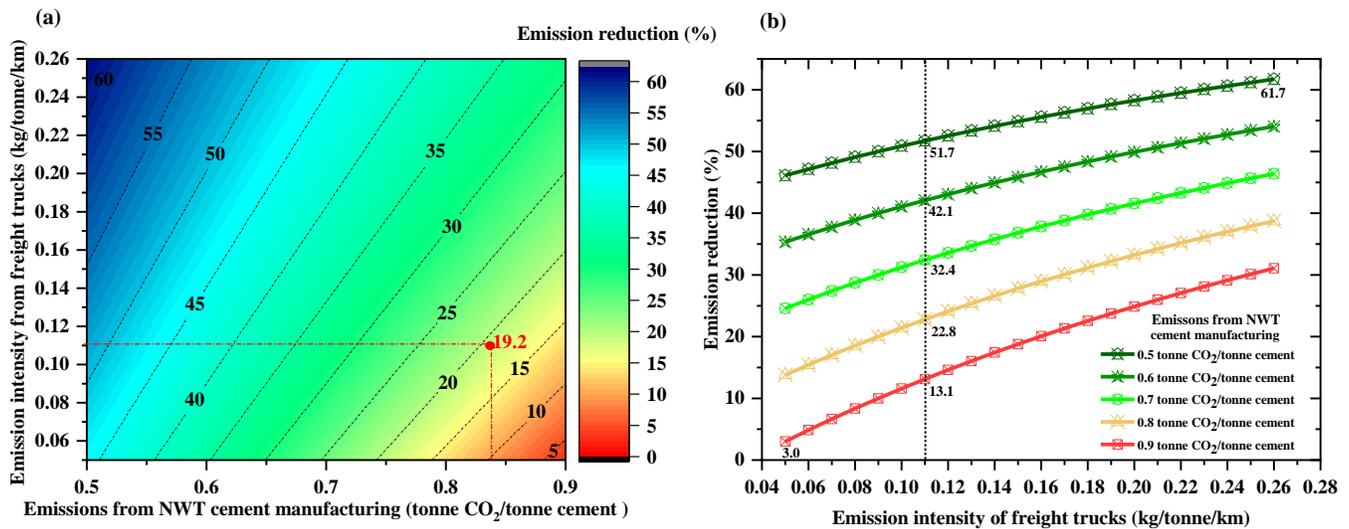


Fig. 11 Estimated emission reduction of producing cement in NWT compared with importing from other provinces.

In summary, manufacturing cement locally in the NWT can avoid long-distance transportation and has great potential to reduce CO₂ emissions when compared with importing cement from other provinces. This is significant for helping the local mining and construction industries to reduce the carbon footprint related to cement consumption. In addition to the environmental benefit, locally manufactured cement may also bring economic benefits to the NWT. For example, it can help reduce the cost of long-distance transportation, increase the value of local geological materials (i.e., limestone, clay, gypsum, and REE mine waste), diversify the local economy, and create employment opportunities.

3.8. Limitations and future work

This study confirmed that the raw materials and mine waste from the NWT are suitable for cement manufacturing, which can contribute significantly to help the local mining and construction industries reduce the emissions and costs related to cement consumption. Despite the great contribution, this work still has its limitations. For example, burnability is an important index indicate how easily the raw materials react with each other to form desired cement clinker (Aguirre Castillo et al., 2023). However, it was not investigated because the cement manufacturing process in a static furnace in a laboratory was different from that in a rotary kiln for industrial scale production. This difference may affect the burnability of cement raw meal. In the future, the burnability of cement raw meal in a rotary kiln should be investigated before starting industrial scale production. In addition, this study produced a prototype Portland cement, which is still emission-intensive (~ 0.8 tonne CO₂/tonne cement (He et al., 2019)). More studies should be conducted to explore the production of low carbon cement (e.g., limestone calcined clay cement (Sharma et al., 2021)) with local raw materials from the NWT.

330 **4. Conclusions**

331 This study explored the feasibility of using the local raw materials (i.e., limestone, clay, and gypsum) and rare earth element
332 (REE) tailings for manufacturing cement in the Northwest Territories (NWT) and evaluated the performance of cement
333 manufactured with the raw materials from the NWT. The raw materials were crushed, pulverized, and their oxide compositions
334 were determined. Then limestone, clay, and REE tailings were proportioned based on the oxide compositions. After that, raw
335 meals were prepared, calcined, and rapidly cooled to get the cement clinker, which was ground with the addition of 5% gypsum
336 to get the NWT cement. At last, cement characterization and performance evaluation (including setting time, workability,
337 hydration reaction, volume stability, and mechanical strength tests) were conducted to examine if they meet the standard
338 specification for Portland cement. The main conclusions are enumerated as follows:

- 339 (1) For the first time, cement was successfully prepared with the local raw materials (i.e., limestone, clay, and gypsum)
340 and REE tailings from the NWT.
- 341 (2) The chemical compositions of NWT cement met the Canadian standard specification for Portland cement.
- 342 (3) NWT cement-based samples showed better workability and similar volume stability when compared with commercial
343 OPC-based samples.
- 344 (4) NWT cement-based samples set slower and had lower early-age (e.g., 1 day) strength when compared with commercial
345 OPC-based samples due to their slower hydration reaction; however, they still met the standard specification.
- 346 (5) Concrete samples made with NWT cement achieved comparable strength of commercial OPC-based concrete at 7 and
347 28 days.
- 348 (6) Producing cement locally in the NWT has the potential to reduce CO₂ emissions in a range of ~3.0% to ~61.7% when
349 compared with importing cement from other provinces.

350 Based on this study, it can be concluded that the raw materials and mine waste available in the NWT are appropriate for cement
351 manufacturing. In addition, locally manufacturing cement would provide a more sustainable solution for cement acquisition
352 and mine waste management, which can contribute significant to the local mining industry.

353 **Declaration of Competing Interest**

354 None.

355 **Acknowledgments**

356 This study was funded by the research project (RES0058395) from Northwest Territories Geological Survey and the Natural
357 Sciences and Engineering Research Council of Canada (NSERC RGPIN-2017-05537).

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