
21 Water Softening

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WATER HARDNESS

Hardness in water is caused by the presence of certain positively charged metallic ions in solution in the water. The most common of these hardness-causing ions are calcium and magnesium; others include iron, strontium, and barium. The two primary constituents of water that determine the hardness of water are calcium and magnesium. If the concentration of these elements in the water is known, the total hardness of the water can be calculated. To make this calculation, the equivalent weights of calcium, magnesium, and calcium carbonate must be known; the equivalent weights are given below.

Equivalent Weights	
Calcium (Ca)	20.04
Magnesium (Mg)	12.15
Calcium carbonate (CaCO_3)	50.045

CALCULATING CALCIUM HARDNESS AS CaCO_3

The hardness (in mg/L as CaCO_3) for any given metallic ion is calculated using Equation 21.1.

$$\frac{\text{calcium hardness (mg/L) as } \text{CaCO}_3}{\text{equivalent weight of } \text{CaCO}_3} = \frac{\text{calcium (mg/L)}}{\text{equivalent weight of calcium}} \quad (21.1)$$

Example 21.1

Problem

A water sample has calcium content of 51 mg/L. What is this calcium hardness expressed as CaCO_3 ?

Solution

Referring to Equation 21.1:

$$\begin{aligned}\frac{x \text{ mg/L}}{50.045} &= \frac{51 \text{ mg/L}}{20.04} \\ x &= \frac{51 \times 50.045}{20.45} \\ &= 124.8 \text{ mg/L Ca as CaCO}_3\end{aligned}$$

Example 21.2*Problem*

The calcium content of a water sample is 26 mg/L. What is this calcium hardness expressed as CaCO₃?

Solution

Again referring to Equation 21.1:

$$\begin{aligned}\frac{x \text{ mg/L}}{50.045} &= \frac{26 \text{ mg/L}}{20.04} \\ x &= \frac{26 \times 50.045}{20.45} \\ &= 64.9 \text{ mg/L Ca as CaCO}_3\end{aligned}$$

CALCULATING MAGNESIUM HARDNESS AS CaCO₃

To calculate magnesium hardness, we use Equation 21.2:

$$\frac{\text{magnesium hardness (mg/L) as CaCO}_3}{\text{equivalent weight of CaCO}_3} = \frac{\text{magnesium (mg/L)}}{\text{equivalent weight of magnesium}} \quad (21.2)$$

Example 21.3*Problem*

A sample of water contains 24 mg/L magnesium. Express this magnesium hardness as CaCO₃.

Solution

Referring to Equation 21.2:

$$\begin{aligned}\frac{x \text{ mg/L}}{50.045} &= \frac{24 \text{ mg/L}}{12.15} \\ x &= \frac{24 \times 50.045}{12.15} \\ &= 98.9 \text{ mg/L}\end{aligned}$$

Example 21.4*Problem*

The magnesium content of a water sample is 16 mg/L. Express this magnesium hardness as CaCO₃.

Solution

Again referring to Equation 21.2:

$$\begin{aligned}\frac{x \text{ mg/L}}{50.045} &= \frac{16 \text{ mg/L}}{12.15} \\ x &= \frac{16 \times 50.045}{12.15} \\ &= 65.9 \text{ mg/L Mg as CaCO}_3\end{aligned}$$

CALCULATING TOTAL HARDNESS

Calcium and magnesium ions are the primary cause of hardness in water. To find total hardness, we simply add the concentrations of calcium and magnesium ions, expressed in terms of calcium carbonate (CaCO_3):

$$\begin{aligned}\text{Total hardness (mg/L) as CaCO}_3 &= \text{calcium hardness (mg/L) as CaCO}_3 + \\ &\quad \text{magnesium hardness (mg/L) as CaCO}_3\end{aligned}\tag{21.3}$$

Example 21.5*Problem*

A sample of water has calcium content of 70 mg/L as CaCO_3 and magnesium content of 90 mg/L as CaCO_3 .

Solution

Referring to Equation 21.3:

$$\begin{aligned}\text{Total hardness (mg/L)} &= 70 \text{ mg/L} + 90 \text{ mg/L} \\ &= 160 \text{ mg/L as CaCO}_3\end{aligned}$$

Example 21.6*Problem*

Determine the total hardness as CaCO_3 of a sample of water that has calcium content of 28 mg/L and magnesium content of 9 mg/L.

Solution

Express calcium and magnesium in terms of CaCO_3 :

$$\begin{aligned}\frac{\text{calcium hardness (mg/L) as CaCO}_3}{\text{equivalent weight of CaCO}_3} &= \frac{\text{calcium (mg/L)}}{\text{equivalent weight of calcium}} \\ \frac{x \text{ mg/L}}{50.045} &= \frac{28 \text{ mg/L}}{20.04} \\ x &= 69.9 \text{ mg/L Mg as CaCO}_3\end{aligned}$$

$$\frac{\text{magnesium hardness (mg/L) as CaCO}_3}{\text{equivalent weight of CaCO}_3} = \frac{\text{magnesium (mg/L)}}{\text{equivalent weight of magnesium}}$$

$$\frac{x \text{ mg/L}}{50.045} = \frac{9 \text{ mg/L}}{12.15}$$

$$x = 37.1 \text{ mg/L Mg as CaCO}_3$$

Now, total hardness can be calculated using Equation 21.3:

$$\begin{aligned} \text{Total hardness (mg/L)} &= 69.9 \text{ mg/L} + 37.1 \text{ mg/L} \\ &= 107 \text{ mg/L as CaCO}_3 \end{aligned}$$

CALCULATING CARBONATE AND NONCARBONATE HARDNESS

As mentioned, total hardness is comprised of calcium and magnesium hardness. Once total hardness has been calculated, it is sometimes used to determine another expression hardness — carbonate and noncarbonate. When hardness is numerically greater than the sum of bicarbonate and carbonate alkalinity, that amount of hardness equivalent to the total alkalinity (both in units of mg CaCO₃/L) is referred to as the *carbonate hardness*; the amount of hardness in excess of this is the *noncarbonate hardness*. When the hardness is numerically equal to or less than the sum of carbonate and noncarbonate alkalinity, all hardness is carbonate hardness, and noncarbonate hardness is absent.

Again, the total hardness is comprised of carbonate hardness and noncarbonate hardness:

$$\text{Total hardness} = \text{carbonate hardness} + \text{noncarbonate hardness} \quad (21.4)$$

When the alkalinity (as CaCO₃) is greater than the total hardness, all the hardness is carbonate hardness:

$$\text{Total hardness (mg/L) as CaCO}_3 = \text{carbonate hardness (mg/L) as CaCO}_3 \quad (21.5)$$

When the alkalinity (as CaCO₃) is less than the total hardness, then the alkalinity represents carbonate hardness and the balance of the hardness is noncarbonate hardness:

$$\begin{aligned} \text{Total hardness (mg/L) as CaCO}_3 &= \text{carbonate hardness (mg/L) as CaCO}_3 + \\ &\quad \text{noncarbonate hardness (mg/L) as CaCO}_3 \end{aligned} \quad (21.6)$$

When carbonate hardness is represented by the alkalinity:

$$\begin{aligned} \text{Total hardness (mg/L) as CaCO}_3 &= \text{alkalinity (mg/L) as CaCO}_3 + \\ &\quad \text{noncarbonate hardness (mg/L) as CaCO}_3 \end{aligned} \quad (21.7)$$

Example 21.7

Problem

A water sample contains 110 mg/L alkalinity as CaCO₃ and 105 mg/L total hardness as CaCO₃. What is the carbonate and noncarbonate hardness of the sample?

Solution

Because the alkalinity is greater than the total hardness, all the hardness is carbonate hardness:

$$\text{Total hardness (mg/L) as CaCO}_3 = \text{Carbonate hardness (mg/L) as CaCO}_3$$

$$105 \text{ mg/L as CaCO}_3 = \text{Carbonate hardness}$$

No noncarbonate hardness is present in this water.

Example 21.8*Problem*

The alkalinity of a water sample is 80 mg/L as CaCO₃. If the total hardness of the water sample is 112 mg/L as CaCO₃, what is the carbonate and noncarbonate hardness (in mg/L as CaCO₃)?

Solution

Alkalinity is less than total hardness; therefore, both carbonate and noncarbonate hardness will be present in the hardness of the sample. Referring to Equation 21.6,

$$112 \text{ mg/L} = 80 \text{ mg/L} - x \text{ mg/L}$$

$$112 \text{ mg/L} - 80 \text{ mg/L} = x \text{ mg/L}$$

$$x = 32 \text{ mg/L noncarbonate hardness}$$

ALKALINITY DETERMINATION

Alkalinity measures the acid-neutralizing capacity of a water sample. It is an aggregate property of the water sample and can be interpreted in terms of specific substances only when a complete chemical composition of the sample is also performed. The alkalinity of surface waters is primarily due to the carbonate, bicarbonate, and hydroxide content and is often interpreted in terms of the concentrations of these constituents. The higher the alkalinity, the greater the capacity of the water to neutralize acids; conversely, the lower the alkalinity, the less the neutralizing capacity. To detect the different types of alkalinity, the water is tested for phenolphthalein and total alkalinity, using Equation 21.8 and Equation 21.9:

$$\text{Phenolphthalein alkalinity (mg/L) as CaCO}_3 = \frac{A \times N \times 50,000}{\text{mL of sample}} \quad (21.8)$$

$$\text{Total alkalinity (mg/L) as CaCO}_3 = \frac{B \times N \times 50,000}{\text{mL of sample}} \quad (21.9)$$

where

A = titrant (mL) used to pH 8.3

B = titrant (mL) used to titrate to pH 4.5

N = normality of the acid (0.02 N H₂SO₄ for this alkalinity test)

50,000 = a conversion factor to change the normality into units of CaCO₃

Example 21.9*Problem*

A 100-mL water sample is tested for phenolphthalein alkalinity. If 1.3-mL titrant is used to pH 8.3 and the sulfuric acid solution has a normality of 0.02 *N*, what is the phenolphthalein alkalinity of the water?

Solution

Referring to Equation 21.8:

$$\begin{aligned}\text{Phenolphthalein alkalinity (mg/L as CaCO}_3\text{)} &= \frac{A \times N \times 50,000}{\text{mL of sample}} \\ &= \frac{1.3 \text{ mL} \times 0.02 \text{ N} \times 50,000}{100 \text{ mL}} \\ &= 13 \text{ mg/L as CaCO}_3\end{aligned}$$

Example 21.10*Problem*

A 100-mL sample of water is tested for alkalinity. The normality of the sulfuric acid used for titrating is 0.02 *N*. If 0 mL is used to pH 8.3, and 7.6 mL titrant is used to pH 4.5, what is the phenolphthalein and total alkalinity of the sample?

Solution

$$\begin{aligned}\text{Phenolphthalein alkalinity (mg/L as CaCO}_3\text{)} &= \frac{0 \text{ mL} \times 0.02 \text{ N} \times 50,000}{100 \text{ mL}} \\ &= 0 \text{ mg/L}\end{aligned}$$

$$\begin{aligned}\text{Total alkalinity (mg/L as CaCO}_3\text{)} &= \frac{7.6 \text{ mL} \times 0.02 \text{ N} \times 50,000}{100 \text{ mL}} \\ &= 76 \text{ mg/L}\end{aligned}$$

DETERMINING BICARBONATE, CARBONATE, AND HYDROXIDE ALKALINITY

Interpretation of phenolphthalein and total alkalinity test results (assuming all of the alkalinity found is due to carbonate, bicarbonate, or hydroxide) can be made using calculations based on the values given in Table 21.1.

Example 21.11*Problem*

A water sample is tested for phenolphthalein and total alkalinity. If the phenolphthalein alkalinity is 10 mg/L as CaCO₃ and the total alkalinity is 52 mg/L as CaCO₃, what are the bicarbonate, carbonate, and hydroxide alkalinities of the water?

TABLE 21.1
Interpretation of Results Values

Results of Titration	Alkalinity (mg/L as CaCO ₃)		
	Bicarbonate Alkalinity	Carbonate Alkalinity	Hydroxide Alkalinity
P = 0	T	0	0
P < ½ T	T – 2P	2P	0
P = ½ T	0	2P	0
P > ½ T	0	2T – 2P	2P – T
P = T	0	0	T

Note: P = phenolphthalein alkalinity; T = total alkalinity.

Source: APHA, *Standard Methods*, Vol. 19, American Public Health Association, Washington, D.C., 1995, p. 2–28.

Solution

Based on titration test results, phenolphthalein alkalinity (10 mg/L) is less than half of the total alkalinity (52 mg/L ÷ 2 = 26 mg/L; see Table 21.1); therefore, each type of alkalinity is calculated as follows:

$$\begin{aligned}
 \text{Bicarbonate alkalinity} &= T - 2P \\
 &= 52 \text{ mg/L} - 2(10 \text{ mg/L}) \\
 &= 52 \text{ mg/L} - 20 \text{ mg/L} \\
 &= 32 \text{ mg/L as CaCO}_3
 \end{aligned}$$

$$\begin{aligned}
 \text{Carbonate alkalinity} &= 2P \\
 &= 2(10 \text{ mg/L}) \\
 &= 20 \text{ mg/L as CaCO}_3
 \end{aligned}$$

$$\text{Hydroxide alkalinity} = 0 \text{ mg/L as CaCO}_3$$

Example 21.12

Problem

Results of alkalinity titrations on a water sample are as follows:

Sample was 100 mL
 1.4 mL titrant was used to pH 8.3
 2.4 mL total titrant was used to pH 4.5
 Acid normality was 0.02 N H₂SO₄

What is the phenolphthalein, total bicarbonate, carbonate and hydroxide alkalinity?

Solution

$$\text{Phenolphthalein alkalinity (mg/L as CaCO}_3\text{)} = \frac{1.4 \text{ mL} \times 0.02 \text{ N} \times 50,000}{100 \text{ mL}}$$

$$= 14 \text{ mg/L as CaCO}_3$$

$$\text{Total alkalinity (mg/L as CaCO}_3\text{)} = \frac{2.4 \text{ mL} \times 0.02 \text{ N} \times 50,000}{100 \text{ mL}}$$

$$= 24 \text{ mg/L as CaCO}_3$$

Now use Table 21.1 to calculate the other alkalinity constituents ($P > \frac{1}{2} T$):

$$\text{Bicarbonate alkalinity} = 0 \text{ mg/L as CaCO}_3$$

$$\text{Carbonate alkalinity} = 2T - 2P$$

$$= 2(24 \text{ mg/L}) - 2(14 \text{ mg/L})$$

$$= 20 \text{ mg/L as CaCO}_3$$

$$\text{Hydroxide alkalinity} = 2P - T$$

$$= 2(14 \text{ mg/L}) - (24 \text{ mg/L})$$

$$= 4 \text{ mg/L as CaCO}_3$$

LIME DOSAGE CALCULATION FOR REMOVAL OF CARBONATE HARDNESS

The lime–soda ash water-softening process uses lime, Ca(OH)_2 , and soda ash, Na_2CO_3 , to precipitate hardness from solution. Carbonate hardness (calcium and magnesium bicarbonates) is complexed by lime. Noncarbonate hardness (calcium and magnesium sulfates or chlorides) requires the addition of soda ash for precipitation. The molecular weights of various chemicals and compounds used in lime–soda ash softening calculations are as follows:

Chemical or Compound	Molecular Weight
Quicklime (CaO)	56
Hydrated lime (Ca(OH)_2)	74
Magnesium (Mg^{2+})	24.3
Carbon dioxide (CO_2)	44
Magnesium hydroxide (Mg(OH)_2)	58.3
Soda ash (Na_2CO_3)	100
Alkalinity (as CaCO_3)	100
Hardness (as CaCO_3)	100

To calculate quicklime or hydrated lime dosage (mg/L), use Equation 21.10:

$$\text{Quicklime (CaO) feed (mg/L)} = \frac{(A + B + C + D) \times 1.15}{\frac{\% \text{ purity of lime}}{100}} \quad (21.10)$$

where

$A = \text{CO}_2$ in source water (mg/L as $\text{CO}_2 \times 56/44$)

$B =$ bicarbonate alkalinity removed in softening (mg/L as $\text{CaCO}_3 \times 56/100$)

$C =$ hydroxide alkalinity in softener effluent (mg/L as $\text{CaCO}_3 \times 56/100$)

$D =$ magnesium removed in softening (mg/L as $\text{Mg}^{2+} \times 56/24.3$)

1.15 = excess lime dosage (using 15% excess)

Note: For hydrated lime dosage, use Equation 21.10 as given for quicklime, except substitute 74 for 56 when determining A , B , C , and D .

Example 21.13

Problem

A water sample has a carbon dioxide content of 4 mg/L as CO_2 , total alkalinity of 130 mg/L as CaCO_3 , and magnesium content of 26 mg/L as Mg^{2+} . Approximately how much quicklime ($\text{CaO} \times 90\%$ purity) will be required for softening? (Assume 15% excess lime.)

Solution

Calculate the A to D factors:

$$\begin{aligned} A &= \text{CO}_2 \text{ (mg/L)} \times (56/44) & C &= 0 \text{ mg/L} \\ &= 4 \text{ mg/L} \times (56/44) \\ &= 5 \text{ mg/L} & D &= \text{Mg}^{2+} \text{ (mg/L)} \times (56/24.3) \\ B &= \text{Alkalinity (mg/L)} \times (56/100) & &= 26 \text{ mg/L} \times (56/24.3) \\ &= 130 \text{ mg/L} \times (56/100) & &= 60 \text{ mg/L} \\ &= 73 \text{ mg/L} \end{aligned}$$

Calculate the estimated quicklime dosage:

$$\begin{aligned} \text{Quicklime dosage (mg/L)} &= \frac{(5 \text{ mg/L} + 73 \text{ mg/L} + 0 + 60 \text{ mg/L}) \times 1.15}{0.90} \\ &= 176 \text{ mg/L CaO} \end{aligned}$$

Example 21.14

Problem

The characteristics of a water sample are as follows: 4 mg/L CO_2 as CO_2 , 175 mg/L total alkalinity as CaCO_3 , and 20 mg/L magnesium as Mg^{2+} . What is the estimated hydrated lime (Ca(OH)_2) (90% pure) dosage required for softening (in mg/L)? (Assume 15% excess lime.)

Solution

Determine the A to D factors:

$$\begin{aligned}
 A &= \text{CO}_2 \text{ (mg/L)} \times (74/44) & C &= 0 \text{ mg/L} \\
 &= 4 \text{ mg/L} \times (74/44) \\
 &= 7 \text{ mg/L} & D &= \text{Mg}^{2+} \text{ (mg/L)} \times (74/24.3) \\
 B &= \text{Alkalinity (mg/L)} \times (74/100) & &= 20 \text{ mg/L} \times (74/24.3) \\
 &= 175 \text{ mg/L} \times (74/100) & &= 61 \text{ mg/L} \\
 &= 130 \text{ mg/L}
 \end{aligned}$$

Calculate the estimated hydrated lime dosage:

$$\begin{aligned}
 \text{Hydrated lime dosage (mg/L)} &= \frac{(7 \text{ mg/L} + 130 \text{ mg/L} + 0 + 61 \text{ mg/L}) \times 1.15}{0.90} \\
 &= 253 \text{ mg/L Ca(OH)}_2
 \end{aligned}$$

CALCULATION FOR REMOVAL OF NONCARBONATE HARDNESS

Soda ash is used for precipitation and removal of noncarbonate hardness. To calculate the soda ash dosage required, we use, in combination, Equation 21.11 and Equation 21.12:

$$\begin{aligned}
 \text{Total hardness (mg/L as CaCO}_3\text{)} &= \text{carbonate hardness (mg/L as CaCO}_3\text{)} + \\
 &\quad \text{noncarbonate hardness (mg/L as CaCO}_3\text{)} \quad (21.11)
 \end{aligned}$$

$$\text{Soda ash (Na}_2\text{CO}_3\text{) (mg/L)} = (\text{noncarbonate hardness (mg/L as CaCO}_3\text{)}) \times (106/100) \quad (21.12)$$

Example 21.15

Problem

A water sample has a total hardness of 250 mg/L as CaCO₃ and a total alkalinity of 180 mg/L. What soda ash dosage will be required to remove the noncarbonate hardness (in mg/L)?

Solution

Calculate the noncarbonate hardness using Equation 21.11:

$$\begin{aligned}
 \text{Total hardness (mg/L as CaCO}_3\text{)} &= 250 \text{ mg/L} - 180 \text{ mg/L} = x \text{ mg/L} \\
 x &= 70 \text{ mg/L}
 \end{aligned}$$

Calculate the soda ash required using Equation 21.12:

$$\begin{aligned}
 \text{Soda ash (Na}_2\text{CO}_3\text{) (mg/L)} &= 70 \text{ mg/L} \times (106/100) \\
 &= 74.2 \text{ mg/L soda ash}
 \end{aligned}$$

Example 21.16*Problem*

Calculate the soda ash required (in mg/L) to soften water if the water has a total hardness of 192 mg/L and a total alkalinity of 103 mg/L.

Solution

Determine noncarbonate hardness:

$$192 \text{ mg/L} = 103 \text{ mg/L} + x \text{ mg/L}$$

$$192 \text{ mg/L} - 103 \text{ mg/L} = x$$

$$89 \text{ mg/L} = x$$

Calculate soda ash required:

$$\text{Soda ash (mg/L)} = (89 \text{ mg/L} \times 106)/100$$

$$= 94 \text{ mg/L soda ash}$$

RECARBONATION CALCULATION

Recarbonation involves the reintroduction of carbon dioxide into the water, either during or after lime softening, lowering the pH of the water to about 10.4. After the addition of soda ash, recarbonation lowers the pH of the water to about 9.8, promoting better precipitation of calcium carbonate and magnesium hydroxide. Equation 21.13 and Equation 21.14 are used to estimate carbon dioxide dosage.

$$\text{Excess lime (mg/L)} = (A + B + C + D) \times 0.15 \quad (21.13)$$

$$\begin{aligned} \text{Total CO}_2 \text{ dosage (mg/L)} = & \left[\text{Ca (OH)}_2 \text{ excess (mg/L)} \times (44)/74 \right] + \\ & \left[\text{Mg}^{2+} \text{ residual (mg/L)} \times (44)/24.3 \right] \end{aligned} \quad (21.14)$$

Example 21.17*Problem*

The *A*, *B*, *C*, and *D* factors of the excess lime equation have been calculated as follows: *A* = 14 mg/L; *B* = 126 mg/L; *C* = 0; and *D* = 66 mg/L. If the residual magnesium is 5 mg/L, what is the carbon dioxide (in mg/L) required for recarbonation?

Solution

Calculate the excess lime concentration:

$$\text{Excess lime (mg/L)} = (A + B + C + D) \times 0.15$$

$$= (14 \text{ mg/L} + 126 \text{ mg/L} + 0 + 66 \text{ mg/L}) \times 0.15$$

$$= 31 \text{ mg/L}$$

Determine the required carbon dioxide dosage:

$$\begin{aligned}\text{Total CO}_2 \text{ dosage (mg/L)} &= (31 \text{ mg/L} \times 44)/74 + (5 \text{ mg/L} \times 44)/24.3 \\ &= 18 \text{ mg/L} + 9 \text{ mg/L} \\ &= 27 \text{ mg/L}\end{aligned}$$

Example 21.18

Problem

The A , B , C , and D factors of the excess lime equation have been calculated as: $A = 10 \text{ mg/L}$; $B = 87 \text{ mg/L}$; $C = 0$; $D = 111 \text{ mg/L}$. If the residual magnesium is 5 mg/L , what carbon dioxide dosage would be required for recarbonation?

Solution

The excess lime is:

$$\begin{aligned}\text{Excess lime (mg/L)} &= (A + B + C + D) \times 0.15 \\ &= (10 \text{ mg/L} + 87 \text{ mg/L} + 0 + 111 \text{ mg/L}) \times 0.15 \\ &= 208 \times 0.15 \\ &= 31 \text{ mg/L}\end{aligned}$$

The required carbon dioxide dosage for recarbonation is:

$$\begin{aligned}\text{Total CO}_2 \text{ dosage (mg/L)} &= (31 \text{ mg/L} \times 44)/74 + (5 \text{ mg/L} \times 44)/24.3 \\ &= 18 \text{ mg/L} + 9 \text{ mg/L} \\ &= 27 \text{ mg/L CO}_2\end{aligned}$$

CALCULATING FEED RATES

The appropriate chemical dosage for various unit processes is typically determined by laboratory or pilot-scale testing (e.g., jar testing, pilot plant), monitoring, and historical experience. Once the chemical dosage is determined, the feed rate can be calculated using Equation 21.15. Once the chemical feed rate is known, this value must be translated into a chemical feeder setting.

$$\text{Feed rate (lb/day)} = \text{Flow rate (MGD)} \times \text{chemical dose (mg/L)} \times 8.34 \text{ lb/gal} \quad (21.15)$$

To calculate the lb/min chemical required, we use Equation 21.16:

$$\text{Chemical (lb/min)} = \frac{\text{chemical (lb/day)}}{1440 \text{ min/day}} \quad (21.16)$$

Example 21.19*Problem*

Jar tests indicate that the optimum lime dosage is 200 mg/L. If the flow to be treated is 4.0 MGD, what should be the chemical feeder setting in lb/day and lb/min?

Solution

Calculate the lb/day feed rate using Equation 21.15:

$$\begin{aligned}\text{Feed rate (lb/day)} &= \text{Flow rate (MGD)} \times \text{chemical dose (mg/L)} \times 8.34 \text{ lb/gal} \\ &= 200 \text{ mg/L} \times 4.0 \text{ MGD} \times 8.34 \text{ lb/gal} \\ &= 6672 \text{ lb/day}\end{aligned}$$

Convert this feed rate to lb/min:

$$\begin{aligned}\text{Feed rate (lb/min)} &= \frac{6672 \text{ lb/day}}{1440 \text{ min/day}} \\ &= 4.6 \text{ lb/min}\end{aligned}$$

Example 21.20*Problem*

What should be the lime dosage setting (in lb/day and lb/hr) if the optimum lime dosage has been determined to be 125 mg/L and the flow to be treated is 1.1 MGD?

Solution

The lb/day feed rate for lime is:

$$\begin{aligned}\text{Lime (lb/day)} &= \text{lime (mg/L)} \times \text{flow (MGD)} \times 8.34 \text{ lb/gal} \\ &= 125 \text{ mg/L} \times 1.1 \text{ MGD} \times 8.34 \text{ lb/day} \\ &= 1147 \text{ lb/day}\end{aligned}$$

Convert this to a lb/min feed rate:

$$\begin{aligned}\text{Lime (lb/min)} &= \frac{1147 \text{ lb/day}}{24 \text{ hr/day}} \\ &= 48 \text{ lb/hr}\end{aligned}$$

ION EXCHANGE CAPACITY

An ion exchange softener is a common alternative to the use of lime and soda ash for softening water. Natural water sources contain dissolved minerals that dissociate in water to form charged particles called *ions*. Of main concern are the positively charged ions of calcium, magnesium, and

sodium; bicarbonate, sulfate, and chloride are the normal negatively charged ions of concern. An ion exchange medium, called *resin*, is a material that exchanges a hardness-causing ion for another one that does not cause hardness, holds the new ion temporarily, and then releases it when a regenerating solution is poured over the resin. The removal capacity of an exchange resin is generally reported as grains (gr) of hardness removal per cubic foot (ft³) of resin. To calculate the removal capacity of the softener, we use:

$$\text{Exchange capacity (grains)} = \text{Removal capacity (grains/cu ft)} \times \text{media volume (cu ft)} \quad (21.17)$$

Example 21.21

Problem

The hardness removal capacity of an exchange resin is 24,000 grains/cu ft. If the softener contains a total of 70 cu ft of resin, what is the total exchange capacity (in grains) of the softener?

Solution

Referring to Equation 21.17:

$$\begin{aligned} \text{Exchange capacity (grains)} &= 24,000 \text{ grains/cu ft} \times 70 \text{ cu ft} \\ &= 1,680,000 \text{ grains} \end{aligned}$$

Example 21.22

Problem

An ion-exchange water softener has a diameter of 7 ft. The depth of resin is 5 ft. If the resin has a removal capacity of 22-kilograins/cu ft, what is the total exchange capacity of the softener (in grains)?

Solution

Before the exchange capacity of a softener can be calculated, the cu ft resin volume must be known:

$$\begin{aligned} \text{Volume (cu ft)} &= 0.785 \times D^2 \times \text{depth (ft)} \\ &= 0.785 \times 7 \text{ ft} \times 7 \text{ ft} \times 5 \text{ ft} \\ &= 192 \text{ cu ft} \end{aligned}$$

Calculate the exchange capacity of the softener using Equation 21.17:

$$\begin{aligned} \text{Exchange capacity (grains)} &= 22,000 \text{ grains/cu ft} \times 192 \text{ cu ft} \\ &= 4,224,000 \text{ grains} \end{aligned}$$

WATER TREATMENT CAPACITY

To calculate when the resin must be regenerated (based on volume of water treated), we must know the exchange capacity of the softener and the hardness of the water:

$$\text{Water treatment capacity (gal)} = \frac{\text{exchange capacity (grains)}}{\text{hardness (grains/gallon)}} \quad (21.18)$$

Example 21.23*Problem*

An ion-exchange softener has an exchange capacity of 2,455,000 grains. If the hardness of the water to be treated is 18.6 grains/gallon, how many gallons of water can be treated before regeneration of the resin is required?

Solution

Referring to Equation 21.18:

$$\begin{aligned}\text{Water treatment capacity (gal)} &= \frac{2,455,000 \text{ grains}}{18.6 \text{ gpg}} \\ &= 131,989 \text{ gallons water treated}\end{aligned}$$

Example 21.24*Problem*

An ion-exchange softener has an exchange capacity of 5,500,000 grains. If the hardness of the water to be treated is 14.8 grains/gallon, how many gallons of water can be treated before regeneration of the resin is required?

Solution

Again referring to Equation 21.18:

$$\begin{aligned}\text{Water treatment capacity (gal)} &= \frac{5,500,000 \text{ grains}}{14.8 \text{ gpg}} \\ &= 371,622 \text{ gallons water treated}\end{aligned}$$

Example 21.25*Problem*

The hardness removal capacity of an ion-exchange resin is 25 kilograins/cu ft. The softener contains a total of 160 cu ft of resin. If the water to be treated contains 14.0 gpg hardness, how many gallons of water can be treated before regeneration of the resin is required?

Solution

Both the water hardness and the exchange capacity of the softener must be determined before the gallons of water can be calculated:

$$\begin{aligned}\text{Exchange capacity (grains)} &= 25,000 \text{ grains/cu ft} \times 160 \text{ cu ft} \\ &= 4,000,000 \text{ grains}\end{aligned}$$

Calculate the gallons water treated:

$$\begin{aligned}\text{Water treatment capacity (gal)} &= \frac{4,000,000 \text{ grains}}{14.0 \text{ gpg}} \\ &= 285,714 \text{ gallons water treated}\end{aligned}$$

TREATMENT TIME CALCULATION (UNTIL REGENERATION REQUIRED)

After calculating the total number of gallons water to be treated (before regeneration), we can also calculate the operating time required to treat that amount of water:

$$\text{Operating time (hr)} = \frac{\text{water treatment (gal)}}{\text{flow rate (gph)}} \quad (21.19)$$

Example 21.26*Problem*

An ion-exchange softener can treat a total of 642,000 gallons before regeneration is required. If the flow rate treated is 25,000 gph, how many hours of operation do we have before regeneration is required?

Solution

Referring to Equation 21.19:

$$\begin{aligned} \text{Operating time (hr)} &= \frac{\text{water treated (gal)}}{\text{flow rate (gph)}} \\ &= \frac{642,000 \text{ gal}}{25,000 \text{ gph}} \\ &= 25.7 \text{ hr of operation before regeneration} \end{aligned}$$

Example 21.27*Problem*

An ion exchange softener can treat a total of 820,000 gallons of water before regeneration of the resin is required. If the water is to be treated at a rate of 32,000 gph, how many hours of operation are there until regeneration is required?

Solution

Again referring to Equation 21.19:

$$\begin{aligned} \text{Operating time (hr)} &= \frac{820,000 \text{ gal}}{32,000 \text{ gph}} \\ &= 25.6 \text{ hr of operation before regeneration} \end{aligned}$$

SALT AND BRINE REQUIRED FOR REGENERATION

When calcium and magnesium ions replace the sodium ions in the ion exchange resin, the resin can no longer remove the hardness ions from the water. When this occurs, pumping a concentrated solution (10 to 14% sodium chloride solution) on the resin will regenerate it. When the resin is completely recharged with sodium ions, it is ready for softening again. Typically, the salt dosage required to prepare the brine solution ranges from 5 to 15 lb of salt/cu ft of resin. Equation 21.20 is used to calculate the salt required (pounds, lb) and Equation 21.21 is used to calculate brine (gallons):

$$\text{Salt required (lb)} = \text{Salt required (lb/kgains removed)} \times \text{hardness removed (kgains)} \quad (20.20)$$

$$\text{Brine (gal)} = \frac{\text{salt required (lb)}}{\text{brine solution (lb salt/gal brine)}} \quad (21.21)$$

To determine the brine solution (the lb salt per gal brine factor used in Equation 21.21), we must refer to the salt solutions table below:

Salt Solutions Table

NaCl (%)	NaCl (lb/gal)	NaCl/cu ft (lb)
10	0.874	6.69
11	0.990	7.41
12	1.09	8.14
13	1.19	8.83
14	1.29	9.63
15	1.39	10.4

Example 21.28

Problem

An ion-exchange softener removes 1,310,000 grains hardness from the water before the resin must be regenerated. If 0.3 lb salt is required for each kilograin removed, how many pounds of salt will be required for preparing the brine to be used in resin regeneration?

Solution

$$\begin{aligned}
 \text{Salt required (lb)} &= \text{Salt required (lb/1000 grains)} \times \text{hardness removed (kg)} \\
 &= 0.3 \text{ lb salt/kilograins removed} \times 1310 \text{ kilograins} \\
 &= 393 \text{ lb}
 \end{aligned}$$

Example 21.29

Problem

A total of 430 lb of salt is required to regenerate an ion exchange softener. If the brine solution is to be a 12% brine solution, how many gallons of brine will be required? (See Salt Solutions table to determine the lb salt/gal brine for a 12% brine solution.)

Solution

$$\begin{aligned}
 \text{Brine (gal)} &= \frac{\text{salt required (lb)}}{\text{brine solution (lb salt/gal brine)}} \\
 &= \frac{430 \text{ lb salt}}{1.09 \text{ lb salt/gal brine}} \\
 &= 394 \text{ gal of 12\% brine}
 \end{aligned}$$

Thus, 430 lb salt to make up a total of 394 gallons of brine will result in the desired 12% brine solution.