6

Cores

Most simply defined, cores are sand shapes which form the contour of a casting that is not molded with a pattern. Drawing the pattern from the mold limits the casting exterior to a contour that can be freed from the sand vertically as it is done with molding equipment. Forming internal cavities thus depends mainly on cores which can be inserted into a mold of the casting exterior. Through their use in forming complex internal cavities, cores provide the casting process its ability to make the most intricate of shapes, eliminate much machining, and in fact produce shapes which would be impossible to machine. For instance, the water-cooling chamber in internal-combustion engines and the exterior and interior of air-cooled engines require intricate coring, as revealed in Fig. 6.1.
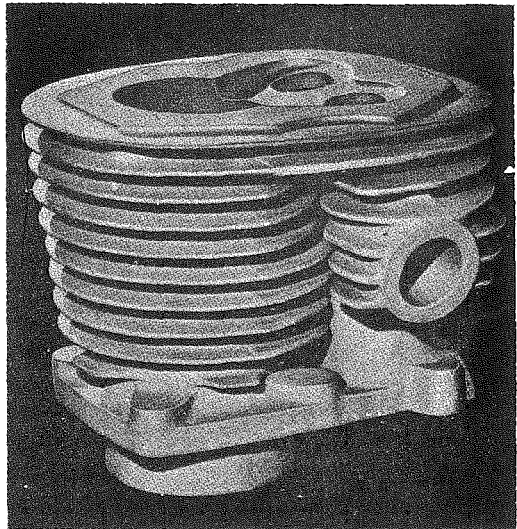

Fig. 6.1   Core-sand casting for air-cooled cylinder block. (*Courtesy of Motor Castings Co.*)

Cores may be made of metal, plaster, and investment and ceramic materials, as well as core sand. To achieve the utmost of intricacy in castings, cores must be collapsible after the metal is poured. Metal cores, used in permanent-mold, or die, casting, do not have collapsibility and therefore have shape limitations. However, sand cores and some other materials do not have this handicap and can therefore produce almost any desired degree of casting intricacy. Sand cores, along with sand molding, are the most frequently used.

In addition to their use for forming internal cavities in castings, cores serve a number of other purposes. Among them are:

1. Complete molds may be assembled of core-sand forms. This is a useful molding practice when the intricacy of the casting is such as to make green-sand molding impractical. The motor block of Fig. 6.1 is a good example.
2. Cores may be used to form a part of a green-sand mold. Pattern contours with back draft or projections which cannot be molded can be formed by placing a core in the mold after the pattern is drawn.
3. Cores strengthen or improve a mold surface.
4. Cores may be used as a part of the gating system. Strainer cores, pouring basins or cups (Chap. 9), and slab cores for building the gating system in large molds are examples of this use.
5. Ram-up cores are used for several purposes. These cores are located on the pattern and rammed up along with the molding sand, the core then forming a part of the mold face. They may be used as a means of locating other cores, as supports for chaplets, to hold chills, or to strengthen the mold.

Some of the uses of cores mentioned above will be considered again later in the chapter.

COREMAKING

Most cores are made of a core sand mixture consisting of sand grains and organic binders which provide green strength, cured strength, and collapsibility. Green strength is required so that core sand may be molded to shape for core making. The core obtains its real strength and hardness when it is cured to develop the bonded strength.

Coremaking is done manually and with machines. Small cores are made by hand-filling core boxes with the sand, usually done at core benches and described as benchwork.

Core boxes can be very simple and consisting of only one piece box. They can also have very complex shape and consisting of multi piece boxes. The sands are squeezed, shaken or blown into the box. The main principle of core blowing is to blow sand air mixture at 560-700 KN/m^2 pressure into core box. The air is ejected from the outlet holes. Core blowing machines can be of many different types, a simple core blower section is shown below.
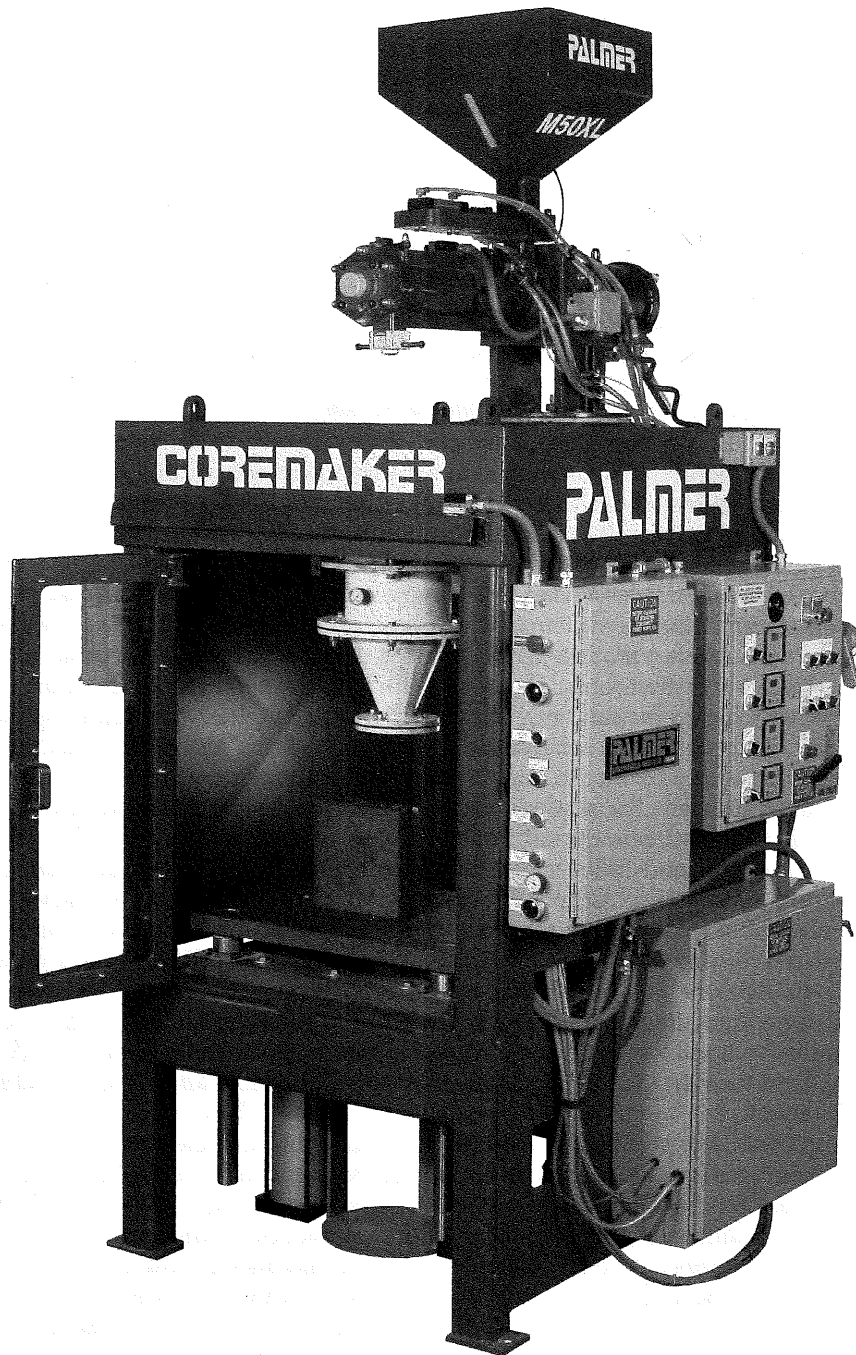

Cross-section of a core blower machine
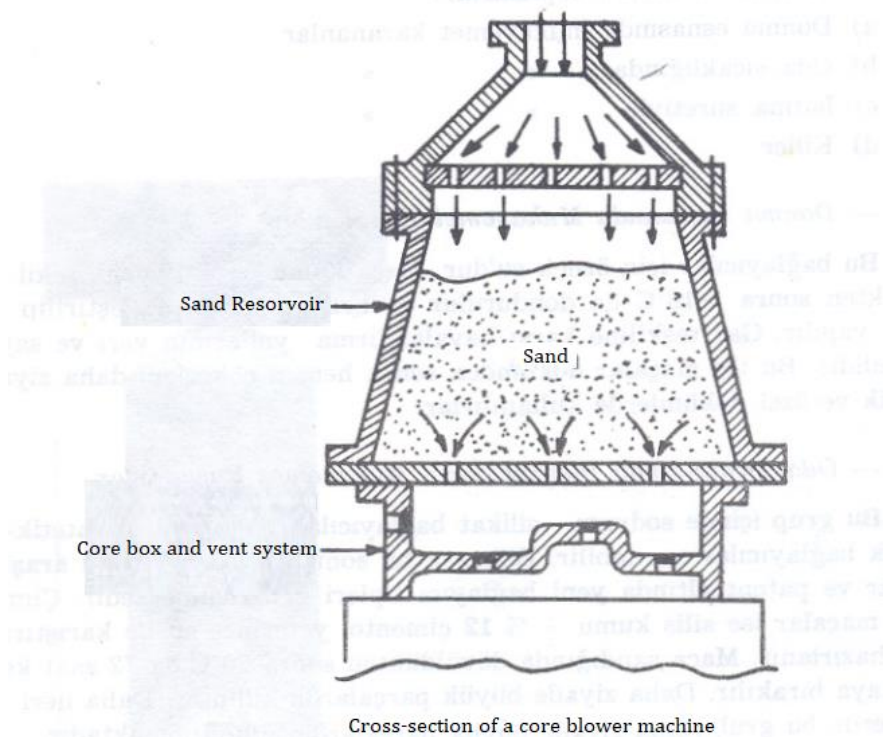
FIGURE 3.70   Core blower. (Courtesy Palmer Manufacturing & Supply.)

7

Core Materials

In molds, the cores must withstand the severest abuse. In spite of being submerged in hot metal, the core must resist erosion, breakage, thermal shock, and metal penetration, as well as retain its dimensional location and produce no casting defects. Yet cores should not be so permanent that their removal from the casting becomes too difficult. These requirements demand that cores be made of suitable materials. Core sands are established as the most versatile of materials for cores. However, cores may be made of metal, ceramics, and green molding sand.

CORE SANDS

Core sands may be simply defined as sand mixtures suitable for cores. To satisfy this definition, the sand mixture is expected to have certain properties, among them:

1. Green strength adequate for the operations of coremaking
2. Response to core baking so that strength, hardness, and other properties are brought out by the baking operation
3. After baking, adequate strength for handling, core setting, and retention of dimensional accuracy
4. Resistance to the action of the molten metal, i.e., erosion, fusion, thermal shock, and venting ability to pass off gases
5. Ease of removal from the solidified casting
6. Retention of desirable properties during periods when baked cores are stored

The above properties pertain particularly to conventional core sands, which are still the most commonly used. Other core-sand mixtures such as shell, furan resin, air-set, and silicate sands need not require baking response since they may not be baked.

CORE-SAND INGREDIENTS

Core-sand mixtures consist of sand grains, binders for green and cured strength, and other additives used for special purposes.

Base Sands

Silica is the basis of most sands used for cores, and zircon, olivine,
others are also used. The word "sand" in foundry terminology n
refer to any granular material of 0.05 to 1.0 mm average particle s
Some properties of the common sands used in core mixtures are compa
in Table 7.1. Of importance are refractory behavior, including fus
point and dimensional and chemical stability with temperature chan
heat-transfer capability, and sieve analysis.

The higher fusion point, higher bulk density, and thermal capacity
zircon and olivine are revealed in Tables 7.1a and b. These may
reasons for their use in cores where silica does not perform satisfactor
Chemical stability refers to inertness, or absence of chemical reaction:

Silica may be reduced by some metals such as magnesium or n
react with others such as iron to form silicates. However, silica is
most widely used base sand.

Core sands should have high purity and should not contain any clay. Round sands are preferred as core sands

Sieve Analysis

Sieve analysis has been discussed in conjunction with molding sa
(Chap. 5). Some typical core-sand sieve analyses are given in Ta
7.2b. The table shows that coarser sands, and those with a narrow s
distribution, have much higher base permeability. Core sands are co
monly 3-sieve sands for this reason. Coarse white silica sands of h
refractoriness are much used for steel foundry cores. The finer ba
and lake sands are more frequently used for cast irons and nonferr
work. Blending of sands, one coarser and one finer, as was shown
Table 5.7, may be used to increase the size distribution and obt
greater strength, with some sacrifice of permeability. The increa
grain surface area in contact when wider grain size distribution preva
4- or 5-sieve sand for example, permits the binders to develop m
strength. For example, from Table 7.2 a mixture of 60 to 65 per c
Michigan No. 3 lake sand and 35 to 40 per cent Michigan No. 4 ba
sand may be used for some core work in gray iron and malleable for
dries. The same blend bonded with clay can be used as a molding sa
as shown in Table 5.7.

Density

Heat-transfer capability, resistance to metal penetration, surface fini
bonded strength, and other properties of cores are much influenced
the bulk density of the aggregate. The bulk density of a silica sa
depends on sieve analysis and particle packing. Possible modes of pa
ing and the densities achieved expressed as per cent of solids are ill
trated in Fig. 7.1. Measurements of bulk density reveal that typi

Table 7.1a   Properties of common granular refractories used in core-sand mixtures

Property	Silica	Zircon	Olivine	Carbon	Chamotte
Vibrated bulk density, lb/cu ft....	110 (95–125)	188	128	68	90–110
Specific gravity...	2.65	4.6–4.7	3.25–3.40	....	2.5–2.7
Melting point, °F..	3119	3452–4622	3200–3450	6400	3100–3200
Mean specific heat	0.275	0.131	0.22–0.33	....	0.25
Temperature, °F..	0–2400	0–2400	0–2800	....	1800
Mean thermal conductivity,Btu/ hr/sq ft/ °F/in..	0.3–0.6	0.9–1.0	0.6–0.70	....	0.6–0.70
Temperature, °F..	0–2800	2000	2000	....	2000
Chemical formula	SiO_2	$ZrSiO_4$	$2MgO \cdot SiO_2$ 84%, $2FeO \cdot SiO_2$ 9%, balance enstatite serpentines, chromite	C	Granular, calcined, aluminous fire clay
Thermal expansion, in./in. to 2000 F	0.020	0.005	0.015	0.008	0.007

Table 7.1b   Typical sieve analysis

	Portage 420		Wedron 5030		No. 70 olivine, ret	Zircon, ret
	Ret*	Cum†	Ret	Cum		
U.S. No. sieve						
20						
30..................	2.2	2.2				
40..................	18.1	20.3	1.2	1.2		
50..................	30.7	51.0	30.4	31.6	26.2	
70..................	25.2	76.2	48.2	79.8	31.0	0.60
100..................	15.7	91.9	17.8	97.6	23.7	11.66
140..................	6.0	97.9	2.0	99.6	9.5	48.02
200..................	1.7	99.6	0.40	....	5.8	39.57
270..................	.....	......	......	....	2.2	
Pan..................	0.4	1000	......	....	1.6	0.15
% AFS clay............	0.50	......	0.50			
AFS No................	51.3	......	51.6	....	69.0	112.3

*Ret—retained on the sieve.

†Cum—cumulative; total on the sieve.

Table 7.2 Sand grains of typical core sands*

| Characteristics	New Jersey		Michigan				Wisconsin				Illinois
			Bank		Lake or dune		Berlin		Doyles-town	Portage screened	Ottawa coarse
	1	6	1	4†	3	7	1	3			
Sieve analysis:											
6											
12											
20	1.7	....	0.10	....	....	0.20	....	....	....	0.60	
30	15.4	....	0.30	0.20	0.1	5.80	0.2	....	....	4.0	11
40	30.1	....	1.10	0.8	1.5	41.6	0.6	1.2	1.0	13.40	74
50	33.5	....	8.7	5.0	17.5	48.2	5.2	12.5	7.0	24.40	14
70	18.8	0.3	27.2	14.0	54.3	4.0	24.5	43.6	32.0	34.40	1
100	1.5	15.3	31.2	29.0	24.9	....	28.9	24.5	36.0	41.60	
140	....	41.6	21.6	36.0	1.10	....	27.6	12.5	18.3	5.20	
200	....	31.6	5.10	10.0	0.10	....	9.40	3.3	4.20	0.40	
270	....	7.8	2.30	4.30	0.10	....	1.6	0.9	0.60	1.80	
Pan	....	3.4	0.30	0.30	0.20	....	0.7	0.8	0.40	0.20	
AFS Fineness, No..............	36.4	124	75	90	54	45	83	68	72	54	30.5
AFS clay, %....................	....	....	2.10	0.7	0.3	0.20	1.3	0.7	0.50	1.0	
Base permeability..............	300	58	70	45	150	260	80	145	120	200	650
Grain shape...................	Rounded	Sub-angular	Sub-angular	Sub-angular	Subangular	Subangular	....	....	....	....	Rounded
Type.........................	Silica	Silica	Bank	Bank	Lake	Lake	Bank	Bank	Silica	Silica	Silica
Typical use..................	Steel, large	Ferrous, brass, light	Blending, nonferrous, light, medium		Gray, malleable, nonferrous	Gray, malleable	Gray, malleable, nonferrous	Gray, malleable, nonferrous	Gray, malleable	Ferrous, steel	Steel
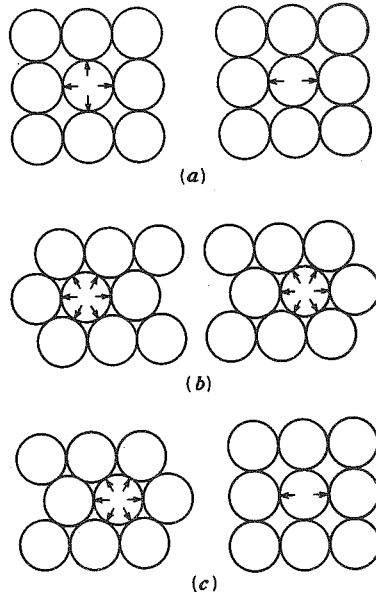
Fig. 7.1 Sand-grain packing configurations.

foundry sands pack to about 55 to 75 per cent solids, commonly about 62 per cent.[1,2] Sieve analysis, particularly size distribution, affects bulk density by raising it as the number of screens over which the sand spread increases from 1 to 10, as shown by Fig. 7.2.

To use Fig. 7.2, a curve relating AFS number and average particle size is needed as in Fig. 7.3. To predict bulk density, the AFS number is calculated from the sieve analysis. The number of screens exceeding 10 per cent retained is determined from the sieve analysis, one additional screen being added for each 10 per cent total on the screens having less than 10 per cent.

The average particle size for the AFS number of the sand is determined from Fig. 7.3. The bulk density is then determined from Fig. 7.2. For example, the P420 sand in Table 7.1b has an AFS number of 51.3. Average particle size from Fig. 7.3 is 0.308 mm. From the sieve analysis it is seen to be a 4½-screen sand. On Fig. 7.2, at 0.308 mm and 4- to 5-screen, spread bulk density is 112 to 114.5 cu ft.

Blending of sands is sometimes practiced to increase bulk density. In blending, the sands used must spread out the sieve analysis if the density is to be increased appreciably. This points to the effectiveness of silica flour (325-mesh) for raising bulk density, as shown in Fig. 7.4. References 1 to 3 and their bibliographies describe further principles in connection with particle packing.
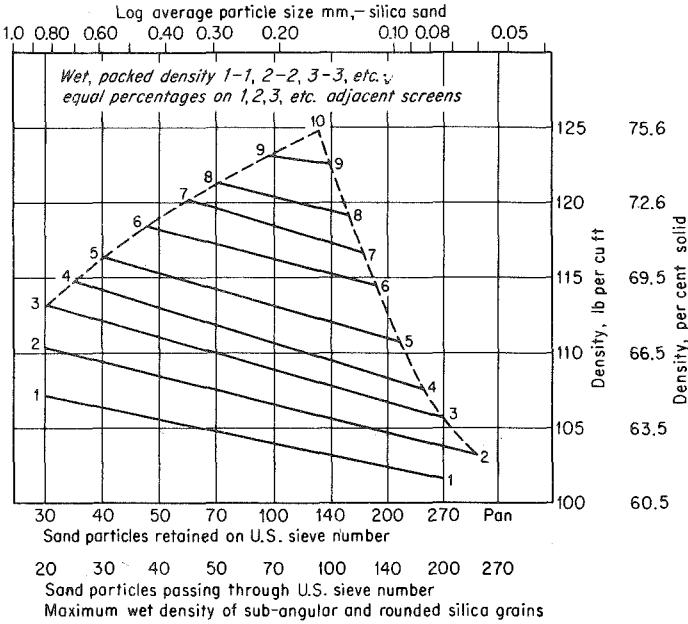
Log average particle size mm,— silica sand

1.0 0.80 0.60   0.40 0.30   0.20   0.10 0.08   0.05

Wet, packed density 1–1, 2–2, 3–3, etc.
equal percentages on 1,2,3, etc. adjacent screens

Density, lb per cu ft

Density, per cent solid

30   40   50   70   100   140   200   270   Pan

Sand particles retained on U.S. sieve number

20   30   40   50   70   100   140   200   270

Sand particles passing through U.S. sieve number

Maximum wet density of sub-angular and rounded silica grains

Fig. 7.2   Empirical relationship of vibrated bulk density of sand to AFS number and average particle size when the sand grains are equally distributed on the number of sieves indicated for each line on the graph.
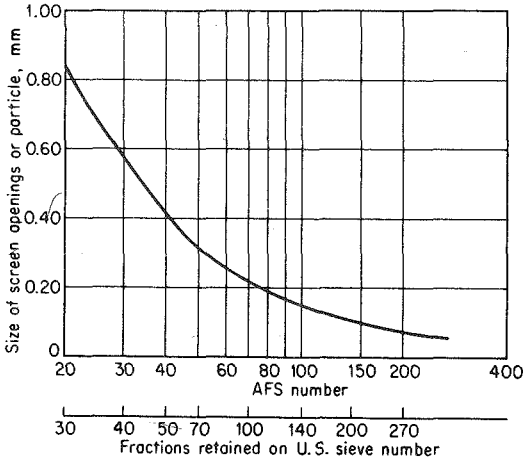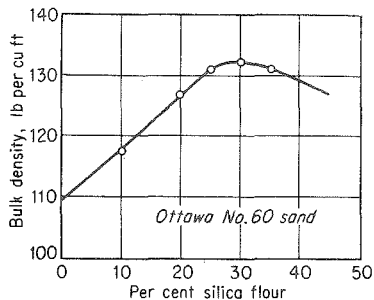
Size of screen openings or particle, mm

20   30   40   60   80 100   150 200   400

AFS number

30   40   50 70   100   140   200   270

Fractions retained on U. S. sieve number

Fig. 7.3   Relationship of AFS number and average particle size.

Fig. 7.4 Effect of silica flour on increasing bulk density of 60 AFS silica sand.

Core Types:
Non-baked, self hardening core making methods

Binder	Binder Level BOS, %	Relative Tensile Strength (1)	Rate of Gas Evolution (1)	Hot Distortion (1)	Ease of Shake-out (2)	Effect of Humidity and Storage (2)	Curing Speed (1)	Strip Time (3)	Resistance to Overcure (2)	Optimum Curing Temperature, °C (°F)	Rebonded Reclaimed Sand (2)	Flowability (2)	Pouring Smoke (1)	Metals to Be Avoided
ORGANIC														
THERMOSETTING														
SHELL Dry blend and hot coat	1–4.5	H	H	M	F	G	H	0.5–6 m	G	260 (550)	G	E	M	
HOT BOX Furan and phenolic	1.5–2	H	H	M	G	G	H	0.5–2 m	F	230 (450)	P	F	M	Steel
WARM BOX	1–1.5	H	L		G	G	H	0.5–1 m	P	175 (350)	P	G	L	
CORE OIL	3.5 (4)	M	H	H	F	G	L	1 h/in	P	205 (400)	E	F	M	
SELF-SETTING														
FURAN NOBAKES														
High nitrogen furan—acid	0.8–1.5	M	M	L	G	G	M	5–45 m	F	27 (80)	P	G	M	Steel
Medium nitrogen furan—acid	0.8–1.5	M-	M	L	G	G	M	5–45 m	F	27 (80)	P	G	M	
Low nitrogen furan—acid	0.8–1.5	M-	M	L	G	G	M	5–45 m	F	27 (80)	P	G	M	
URETHANES														
Alkyd - organometallic	1.0–1.5	M	H	L	F	G	L	10–90 m	E	27 (80)	F	F	H	(5)
Phenolic—pyridine	1.0–1.5	M	H	M	G	F	H	2–20 m	E	27 (80)	P	G	M	
PHENOLIC ACID NOBAKE	0.8–1.	M-H	M-	var	G	G	M+	2–45 m	G+	27 (80)	F-	G	M-	
VAPOR-CURED (COLD BOX)														
Phenolic urethane—amine	0.8–1.5	M	H	M	G	F	H	20–60 s	E	24 (75)	P	G	M	(5)
Phenolic/ester cured	1–2	M	L	H	G	G	H	20–0 s	E	24 (75)	F	G+	M	
Epoxy—SO_2	0.6–1.2	M+	M	M	G	G	H	20–60 s	E	24 (75)	P	G	M	

INORGANIC														
SELF-SETTING														
Sodium silicate—ester cured		L	L	M	P	P	F	15–120 m	F	24 (75)	F	P	L	
Cement—hydraulic cured	8	VL	L	L	P	G		15–120 m		24 (75)	F	F	VL	
Phosphate—oxide cured	2.5–4	M	L	L	G-F	P	F-G	10–60 m	g-g	24 (75)	F	F-	VL	
VAPOR CURED														
Sodium silicate—CO_2	3–5	L	L	L	P	P	P	1/2–2 m	P	24 (75)	F	P	VL	

Notes:
(1) H = hiqh, M = medium, L = low, N = none
(2) E = excellent, G = good, F = fair, P = poor
(3) Rapid strip times require special mixing equipment
(4) Typically 1% oil, 1.5% water and 1% cereal
(5) Iron oxide required for steel

Source: Chemically Bonded Cores & Molds, AFS [65].

TABLE 3.22   Comparison of the Properties of Various Mold and Core Binder Systems

Organic Binders

In this chapter, the word *organic* is used in the traditional scientific manner to mean carbon based. Whereas inorganic refers to compounds made up of elements predominantly from the rest of the periodic table. Unlike the food and retail businesses, organic foundry binders have environmental issues as they release undesirable chemicals such as phenols, benzene, other aromatics, formaldehyde, carbon monoxide, etc., both in gaseous form and in the sand (see EPA listings). Inorganics have much less of an environmental footprint, foundry air is less hazardous and molding aggregates can generally be discarded without further treatment.

Shell Hot Box

The Croning or shell process was developed in Germany during World War II. Originally, the materials were mixed, then dumped onto a pattern and heated to melt and set the binder. As the ingredients were dry, there were numerous problems, the most serious being separation of the ingredients [54, 57]. Special plants hot mix sand (at 300°F) with particles of phenolic novolak resin and a lubricant calcium stearate. During a wet mull, the resin melts and coats the sand grains. An aqueous solution of hexamethylene-tetramine (hexa, a compound of ammonia and formaldehyde) is thoroughly mixed with the sand. The water cools the sand and the coating device and vibratory screens break the lumps. Copious amounts of air circulate to cool the sand on long conveyors until it is free-flowing. Most foundries buy coated shell sand from commercial sand coaters. Shell sand is available in bags with binder levels varying by 0.5% increments from 2 to 4.5% resin. The bags should be stored in dry, cool areas and not stacked too high, otherwise lumps can form. The advantages are

1. Nonflammable.
2. Free flowing sand which is easy to pour in and out of core boxes.
3. Free of volatile organic compounds (VOCs).
4. Easier to handle than the liquid counterparts, with no measuring of ingredients.
5. Quickly formed into dense, strong cores or molds with less pressure than other binders.
6. High hot strength and resistance to decomposition and distortion.
7. Excellent dimensional tolerances.
8. Although the binder levels are higher than other binder systems, the level of gas defects is lower as the cores can be hollow, and the use of a coarser sand improves the permeability so that core gases vent through core prints rather than through the casting.
9. Low nitrogen grades are available for steel castings.
10. Coatings are rarely required, so the cost of refractory, application, drying, labor, and maintenance of all the equipment are avoided.
11. Less sand is required to make thin-walled molds and hollow cores, and the uncured sand that is drained from the curing core is reusable.

Leo Baekeland in New York was the first in 1907 to study the elimination reaction of phenol and formaldehyde to produce polyoxybenzylmethylenglycolanhydride, Eq. (3.9), which became Bakelite, an early plastic, and the precursor of modern novalac resins.

$$C_6H_5OH + CH_2O = H_2O + \left[\vphantom{\Big|} \right]_n \qquad (3.9)$$
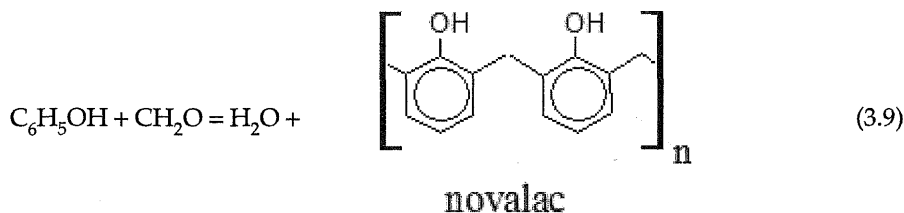
novalac

When the coated sand first contacts the hot pattern [below 500°F (260°C) for larger cores and 525 to 600°F (275 to 315°C) for small solid cores], a number of physical transitions and chemical reactions occur. First, the novalac resin begins to melt, causing the viscosity of the coating to drop, as the hexa decomposes to ammonia and formaldehyde. The resin begins to polymerize and the phenol in the resin reacts with the formaldehyde liberating a small amount of water. The binder flows between the sand grains and bridges lock them together. As the phenol-formaldehyde reaction continues the resin becomes thermosetting and the whole mass is rigid. The color of the sand is now golden yellow, and indicates a strong cured mold. If heat is still applied, the resin cures further, the color turns brown and the sand is weaker. Further heating the sand decomposes the binder, and it turns black. At this point, the surface is burnt and carbonized. Castings in contact with this core will have penetration defects on their surfaces, and/ or core breakage can occur. The best color is dark gold or light brown. Many overcook in the belief less gas is generated later, but less binder is more effective.

The sequence for the foundry process are first, the coated sand is either dumped by gravity or blown from an adjacent storage hopper into contact with a heated pattern plate or core box. The curing reaction takes place from the heated surface inward, and is normally allowed to progress to the point where a crust or shell of desired thickness is formed. At this point, the remaining uncured sand is drained back into the storage hopper usually by inverting the core box and a large section of the core blower. The cured shell mold or core is stripped or ejected. For best results, the process should be highly instrumented with the liberal use of sensors and a programmable controller. Die release agents can be applied every 10 applications. Many foundries block the ends of cores so if metal gets into the core print, it does not fill the core - a run-in defect. A schematic representation of the shell molding process is given in Fig. 3.71. The most authoritative reference on all aspects of the shell process is the AFS publication, *Shell Process Foundry Practice* [64].

The phenol-formaldehyde shell process has found greater application for coremaking than for molding. Its initial attraction as a molding method lay in its capability to hold closer tolerances than greensand molds, while providing improved surface finish. From the outset, its disadvantages were lower productivity, expensive pattern equipment, and higher energy costs. The advent of automated, high-density greensand molding served to swing the balance further away from shell molding as a viable economic process. Nevertheless, steel foundries still employ the process for small rangy castings where shell's high hot strength is an advantage. In addition, the draft on side walls is of the order of $\frac{1}{4}$ degree, so minimal machining is required so casting such as steel toothed bevel gears and truck fifth wheels can be cast in shell molds.

Shell coremaking has been quite another story. Its initial attraction in the 1950s was due to the fact that it offered a means of eliminating the traditional core oils, with their
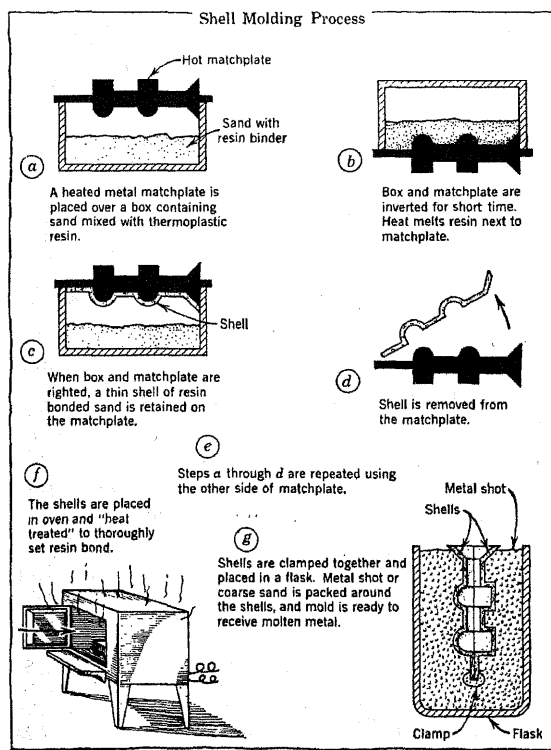
Shell Molding Process

(a) A heated metal matchplate is placed over a box containing sand mixed with thermoplastic resin.

(b) Box and matchplate are inverted for short time. Heat melts resin next to matchplate.

(c) When box and matchplate are righted, a thin shell of resin bonded sand is retained on the matchplate.

(d) Shell is removed from the matchplate.

(e) Steps a through d are repeated using the other side of matchplate.

(f) The shells are placed in oven and "heat treated" to thoroughly set resin bond.

(g) Shells are clamped together and placed in a flask. Metal shot or coarse sand is packed around the shells, and mold is ready to receive molten metal.

Figure 3.71   Forming a shell mold. (From Sahoo [7].)

core blowers, core driers, reinforcing wires, baking ovens, and skilled coremaking labor. The popularity of shell coremaking accelerated rapidly from 1950 onward, peaking in about 1970. Although the Shell Process has declined in popularity, it has benefited from new products such as the low odor–low hexa type. This decline has resulted from at least three factors: (1) the rapid escalation of energy costs beginning in the 1970s, curtailed supplies of natural gas for heating the boxes; (2) environmental regulations dealing with solid waste disposal and the identification of shell sand wastes as sources of free phenol; and (3) the introduction of other fast-cure coremaking binders competitive with the shell process. On the other hand, although cost per ton of coated sand is high, actual consumption per part and sand disposal can be significantly lower, coatings are seldom required, so drying costs and application costs are avoided, finish is excellent so cleaning room costs are lower. Reclaimed sand is not generally used, but the Canadian Foundry Association's Sand Reclamation Committee found in 1991 that shell resin is generally insensitive to surface impurities.

Furan Nobake

The acid catalyzed nobake furan binder system was introduced in 1958 [54, 58]. It consists of two main ingredients: furfuryl alcohol in monomeric form or a low molecular weight polymeric form and an acid to initiate or further polymerization. In 1960, the binder formulation was modified with an acid salt catalyst to use as a hot box core

process. Furfuryl alcohol or 2-furylmethanol ($C_5H_6O_2$) has the $-CH_2OH$ group on the number 2 position of furan. It is made from its aldehyde, a by-product in the sulfuric acid treatment of waste vegetable materials (corn husks, rice husks, sugar cane) to obtain the sugar, xylose. From time to time, there are shortages of furfuryl alcohol, and foundries are forced to switch to another binder until supplies return to normal. Although furfuryl alcohol polymerizes easily, extenders such as urea, formaldehyde, water, phenol or phenolic derivatives, and proprietary chemicals are added to lower the cost. They also increase the viscosity, which does not help when coating sand. Certain ingredients in these extenders are of concern; urea adds nitrogen; phosphoric acid the phosphorus and formaldehyde the free formaldehyde, although modifiers can be added to "scavenge" formaldehyde. Although there are many grades, they are usually classified as low, medium, and high (Table 3.24). Water delays both the cure and the final tensile strength which are reduced approximately in proportion to the water content. The polymerization is accompanied by liberation of more water and might initially produce the polymer shown in Eq. (3.10), but time and UV light cause cross-linking and other changes. It is likely the coordinated double bonds are responsible for the sand's color changes (green to black to brown).

$$ \text{(3.10)} $$
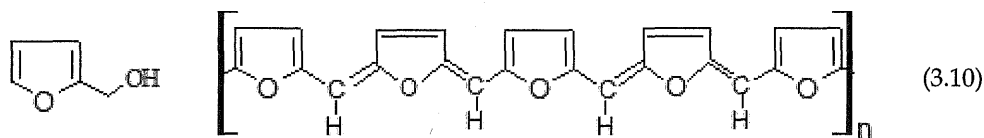
Furfuryl alcohol and a polymer formed with a strong acid catalyst.

Because the binder produces water as a product of the reaction, molds and cores cure from the outside in, i.e., surfaces exposed to air cure first. Molders often use a large nail to feel the depth that the binder has cured, i.e., they are concerned about what they call the "deep set." Consequently, stronger acids are used to optimize cure rate and deep set properties. Acids in the order of increasing reactivity are: 75% phosphoric, 85% phosphoric, toluene sulfonic, xylene sulfonic, and benzene sulfonic. Five to ten percent sulfuric can be added to phosphoric acid to boost its reactivity. Phosphoric acid may become viscous or even crystallize in cold weather, if not warmed. The sulfonic acids are usually diluted by methanol which is flammable.

Although composition and grade selected for the binder will be dictated by the metal to be poured (Table 3.25), the cure time required, the complexity and thickness of the casting, whether and what type of reclamation is to be used. A typical binder level

Grade	% Nitrogen	% Water
Low	0–3	0–5
Medium	2–8	5–15
High	5–11	10–30

Source: AFS [65].

TABLE 3.24 Grades of Furan Nobake Binders

Metal	Class	Suggested Amounts	
		% Nitrogen	% Water
Gray iron	20, 30	5–11	8–15
Gray iron	40, 50, 60	0–4	0–10
Ductile iron	All	0–5	0–8
Steel	All	0	0
Nonferrous*	–	4–11	8–15

*Furan can turn the surface of aluminum castings green.
Source: AFS [65].

TABLE 3.25   Furan Grade for Various Metals

for silica molds is 0.8 to 1.5%, and will depend on the type, shape, and purity of the sand. Cores are usually made with a higher binder level. A good starting binder level is 1.0 resin (1% based on sand), 0.30 catalyst (30% based on binder), and 100 of sand—units are pounds, kilograms, etc.

Catalyst and resin should be stored separately. They should not be mixed in the pure state; only on sand (slow cure time) with the sand first coated with catalyst in a batch mixer for 2 minutes, then the resin added. Reversing the process results in rapid curing and bond failure where the acid meets the sand. In continuous mixers, the catalyst is added before the resin. If there is a need to dilute the catalyst, the catalyst should be added to water. Addition of water to acid (catalyst) is highly exothermic, and a steam explosion will probably occur, throwing acid around. Plastic containers are better temporary storage as acids attack metals. Transport of acid containers is governed by safety rules in most jurisdictions. The materials are all water soluble, so small spills, tools, or even hands can be easily cleaned. Even so, contact with the chemicals and bonded sand should be avoided.

Advantages:

1. High strength for the binder level, high hot strength, but good shakeout due to collapsibility.
2. Excellent flowability.
3. Lower smoke and odor during the casting process than other solvent-based binders.
4. Can be used with all sands but olivine, and any pattern material although furfuryl alcohol may dissolve shellacs, varnish, or paint.
5. Cores can be stored pending need, as the bond has good resistance to humidity.
6. Wide selection of binder formulations to balance cost and performance.
7. Good selection of acids and combinations to control catalytic activity.
8. Low temperature variants available to control curing and coating.
9. Color change indicates rapid cure and warns of insufficient work time.

Disadvantages:

1. Chemicals are irritating to skin and eyes. These acid catalysts are corrosive.
2. Work/strip times very sensitive to temperature.

3. Extenders lower cost but reduce properties.

4. Nitrogen from urea and sulfur from acids complicate the sand reclamation process.

5. Mechanical reclamation causes an acidic sand surface (high ADV).

6. Some formulations contain phenol which can leach into ground water.

Alkyd Urethane Nobake

The urethane nobake and urethane cold box binders are the second and third highest sellers in North America after furan [54, 56]. It was discovered that the isocycanate reacted with core oil, causing the metallic dryer to perform better by forming a urethane. Companies such as ASK (previously Ashland Oil) developed and patented a series of sand binders based on MDI [see Eq. 3.11)] starting in the early 1950s called *air-set* and *cold-set* binders. The drawback with these early binders was a prolonged drying at elevated temperatures. However, from them came better formulations. The current binders have three parts: two co-reactants, one an oil urethane, the other an MDI isocyanate, and a catalyst. Just as furfuryl alcohol was able to polymerize with itself, so can MDI. Isomers of MDI can also polymerize to form polymers of the type $-[-C_6H_4NCO-CH_2-]_n-$. However, resins or vegetable oils containing active phenols $-[-C_6H_3OH-]-$ can react with the MDI polymer in the presence of an amine catalyst to cross link and form a solid urethane Eq (3.11), but not to the degree as for the next binder system.

1-isocyanato-4-[(4-isocyanatophenyl) methyl] benzene or MDI

polymeric MDI

(3.11)
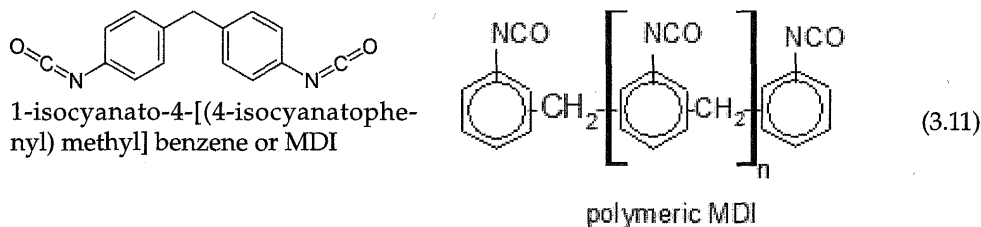
The alkyd urethane nobake binder (also known as oil-urethane or polyester–urethane) consists of three parts. Part A is an oil-type resin or modified vegetable oil with phenyl hydroxyl groups which will form a urethane group with the isocycanate and a catalyst. Many such resins are available commercially. Part A is typically 1.0 to 1.5% BOS (based on sand) for an AFS GFN 55 round grain silica sand. Part B, the catalyst, consists of several amines and a metallic drying agent to facilitate the oxidation reaction, stage two. At one time, lead was the metallic drying agent, but it has largely been replaced by less noxious metals. Strip time can be adjusted from 10 minutes to 4 hours depending on the amine selected and its concentration. Part B should be between 1 to 10% of the resin. Most manufacturers preblend the catalyst with part A, as some pumps are difficult to adjust with sufficient accuracy. Part C is a polyisocyanate, which because of the isocyante group contains 10% by weight nitrogen. Part C should be added at 18 to 20% of Part A. Too much Part C causes gas defects [65]. As Part C reacts with water, its container should be mildly pressured with nitrogen, or the liquid extracted for the process replaced by air that has passed through silica gel to remove atmospheric moisture. Water in the sand (>0.2%) or in Part A will retard the cure and result in loss of strength. Even without a heating stage, small molds and cores can be poured 20 minutes after stripping, larger molds may require 4 to

24 hours. Most washes are compatible once the mold/core has cured, but coating solvents should be evaporated. High atmospheric moisture will increase strip time. Half a percent moisture in the sand can quadruple cure time and reduce tensile strength by a half.

Alkyd urethane binders cure in three stages [54]. The first stage determines the work and strip times and involves a reaction of the hydroxyl group on a phenolic resin with the isocyanate (-NCO) group to form a weak urethane bond. This leaves the sand strong enough for stripping. In the second stage, unsaturated (double) bonds in alkyd resin react with oxygen. If the cure is insufficient, the hot strength of the mold or core is poor. The cure can be improved by heating, with the third stage occurring at 400°F, which is the cross linking of the various polymers.

The alkyd urethane system being less sensitive to conditions has the following advantages:
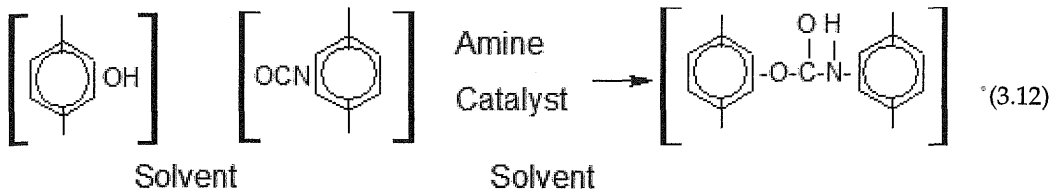
1. Suitable for ferrous and nonferrous metals.
2. Can be mixed in conventional mullers and continuous mixers.
3. The mix is flowable but mild compaction is necessary to achieve good strength.
4. The plasticity of the sand at stage one permits patterns with minimum draft.
5. Strip time is less sensitive to sand type, temperature, moisture, additives, and impurities than other nobake or cold box binders.
6. The temperature and nature of the pattern material affects stripping time, but less so than with other binders.
7. Shakeout characteristics are good and sand is reclaimable.

Disadvantages are:

1. The time between stripping and pouring is longer than other binder systems due to the oxygen cure.
2. Large molds need to be stored several days for the oxygen cure to complete.

Phenolic Urethane Nobake

Although announced in 1970, consumption has grown from 2.7 million pounds in 1970 to 300 million pounds worldwide by 2001 [66]. This binder also has three parts: two co-reactants, polybenzylic-ether-phenolic resin and polyphenyl polyisocyanate (polymeric MDI isocyanate), and an amine catalyst. This time, it's basically the same functional groups but now on two polymers that react together in the presence of a catalyst (usually a pyridine derivative, benzene with one carbon in the ring replaced by nitrogen) to cross link the two polymers and form a solid three-dimensional urethane matrix with no by-products. The reaction in Eq. (3.12) is faster than in the alkyd urethane system, and the sand remains free flowing almost to the end of the working life. The work time is about 75% of the strip time (30 seconds to 30 minutes) but as the reaction is so fast, the sand becomes very rigid and does not yield easily for stripping. Patterns need to be inspected frequently and well maintained. Molds can be poured when the reaction is 80% complete, about 4 hours. As there are no by-products, the sand cures evenly at the same rate in thick and thin sections. Cross-linked chains tend to be short because the binder cures so rapidly, so the cores are sensitive to ambient humidity when stored. It is better to use high-speed mixers in order to take advantage of the short working life [54, 56].

$$\left[\text{◯-OH} \right]_{\text{Solvent}} \quad \left[\text{OCN-◯} \right]_{\text{Solvent}} \quad \begin{array}{c} \text{Amine} \\ \text{Catalyst} \end{array} \rightarrow \left[\text{◯-O-}\overset{O}{\underset{}{C}}\text{-}\overset{H}{\underset{}{N}}\text{-◯} \right] \qquad (3.12)$$

Total binder is typically 0.8 to 1.75% (based on sand or BOS). Part I is the polyphenolic resin and Part II the polymeric MDI. Part II is hydrophilic and needs to be protected from moisture. Although the binder was designed to operate with equal Parts I and II, many foundries use more Part I, often from 52.5 to 60%, as Part II contains most of the nitrogen. According to Ashland, Part II tends to cause lustrous carbon defects in ferrous and nickel castings [56]. The defect appears as wrinkled skin often following flow marks. It is caused by high quantities of carbonaceous decomposition products. These alloys normally need a reducing atmosphere, so this amounts to too much of a good thing. Naro recommends trying shorter, deeper ingates and rapid mold filling with nonturbulent flow, failing these higher pouring temperatures, 2% red Fe_2O_3 with an additional 0.1 to 0.2% binder, or binder solvents made of biodiesel [66]. Red Fe_2O_3 is said to release oxygen into the mold cavity to form carbon monoxide rather than lustrous carbon. Hematite also improves casting surface finish, provides chill, and reduces gas and sand expansion defects.

The amine catalyst, Part III, is selected to fit work/strip times into foundry operations. Fine-tuning is accomplished by adjusting the concentration. Part III is normally between 2 and 9% of the Part I resin. If the addition falls outside this range, a different amine should be used. As the amount of catalyst is very small, the delivery pump should be accurate to ±1%. Improved mixing is achieved by introducing the catalyst into the Part I delivery line just ahead of the discharge into the mixer. The nitrogen content of the binder is between 3.0 and 3.8%, or 0.04% of the sand, at the upper end of the range of low-grade furans.

New formulations and amine catalysts with smaller environmental footprints are constantly being announced and marketed. There are also similar binders, the phenol-free polyether-polyol-urethane and a special low VOC version both used for nonferrous castings. The polyether has as Part I a polyol resin, Part II an MDI isocyanate, and Part III an amine catalyst. The hydroxyl groups are distributed on nonaromatic chains rather than phenol. Both Part I and Part II are hydrophilic and must be protected from moisture during storage and use.

The phenolic urethane nobake being less sensitive to conditions has the following advantages:

1. Suitable for ferrous and nonferrous metals.

2. The mix is flowable and workable almost to the end of the working time but mild compaction is necessary to achieve good strength. The delayed cure means there is no loss of strength even if the full working life is used.

3. There is greater productivity and pattern turnaround as a result of the short period between work and strip times, and the periods are easily adjusted.

4. Phenolic urethane can be used with almost any sand, however, as the catalyst is alkaline low, ADV are preferred, but adjustments to the binder can be made even for mechanically reclaimed sands with high ADV.

5. Aqueous coatings can be applied immediately after stripping as long as they are oven-dried immediately; coatings that light-off should be delayed 10 minutes [56].

6. Sand is easily reclaimable by mechanical means as the coating is relatively brittle. Thermal reclamation requires one million BTU/ton of sand to remove the resin and its residues from the sand. The binder supplies much of the heat.

Disadvantages are:

1. Sand temperature should be controlled within 80 to 90°F (27 to 32°C), and moisture less than 0.2% in winter and 0.1% in summer, otherwise the reaction is delayed.

2. Stripping time is critical, and the mold or core must be stripped while it is still a little plastic, otherwise breakage and sticking occur. Patterns need to be kept clean and release agents should be used. A paint mitten over a rubber glove works well to remove sand and apply release agent. Wooden patterns should be impregnated with the urethane release agent to stabilize the wood and not painted or lacquered as all three parts will dissolve them.

Furan Warm Box

The furan warm box process uses the same coating and production equipment, the same procedures and techniques as the furan and urethane hot box processes (not covered). These hot box processes use ammonium salts rather than the acids in the nobakes. The salt decomposes once exposed to core box temperatures of 400 to 500°F (205 to 260°C) into ammonia and the same acids as in the cold box processes [54, 59, 65]. The additional temperature increases the rate 50,000 times, enough to finish the reaction as the sand approaches the core box temperature, 20 to 40 seconds. Although a fraction of dissolved salt in the mixed sand can initiate the same reactions as the various nobake processes described earlier, the reaction is slow, but proceeds enough to shorten bench life, particularly if the hopper above the core blower is not shielded or cooled. The hot box processes use 1.5 to 2.0% resin (BOS).

The chemistry of the furan warm box process is quite different. The resin component contains very little water, 70% furfuryl alcohol, and may be modified with small amounts of urea-formaldehyde or phenolformaldehyde. Urea is the source of the nitrogen, which can be up to 2.5%, but free formaldehyde is not present. The catalyst is usually a copper salt of toluene sulfonic acid and some copper chloride dissolved in water and methanol. Just as in the hot box process the copper sulfonic acid breaks down into the acid, but at a lower temperature than the ammonium salt. There are several sulfonic acids that can be used to vary the cure speed, bench life, through-cure, and resistance to humidity during storage. Bench life is typically about 8 hours. The mixed sand should not be handled, especially the catalyst. The off gases being low in phenolformaldehyde result in improved air quality. The reaction between the resin and catalyst is quite violent, so pure materials should not be mixed. The best temperatures for the core boxes are between 360 and 400°F (180 and 205°C). The resin has low viscosity, and 1.0 to 1.5% (BOS) is used depending on the sand type and condition, core configuration, the metal to be poured, and shakeout collapsibility required.

The warm box process uses new sands with low moisture and low ADV, although the latter can be compensated for by increasing the amount of catalyst. Mined natural

olivine with its high calcite content should not be used. Any type of mixing system can be used, although blending may be a little more difficult without pumps to add the ingredients slowly. The furan warm box is a pleasure to use.

Advantages:

1. The lower resin content means lower gas emissions and less chance of lustrous carbon. Consequently iron oxide powder feeds on the continuous mixer are not required.

2. The excellent sand flowability allows for a significant reduction in blow pressure (compared to hot box) and potentially larger blow tubes eliminates riffling of sand into blow box cavities. The excellent flowability means less tool wear and high bulk densities that do not require coatings.

3. Although resistance to high relative humidity is excellent, strength, though higher, still falls off starting at about 60% relative humidity (Fig. 3.72).

4. Lower core box temperatures reduce energy consumption, improve operating environment, and cause less distortion and warpage in tooling.

5. No free formaldehyde and no formaldehyde emissions from core boxes and spent sands meet present EPA standards.

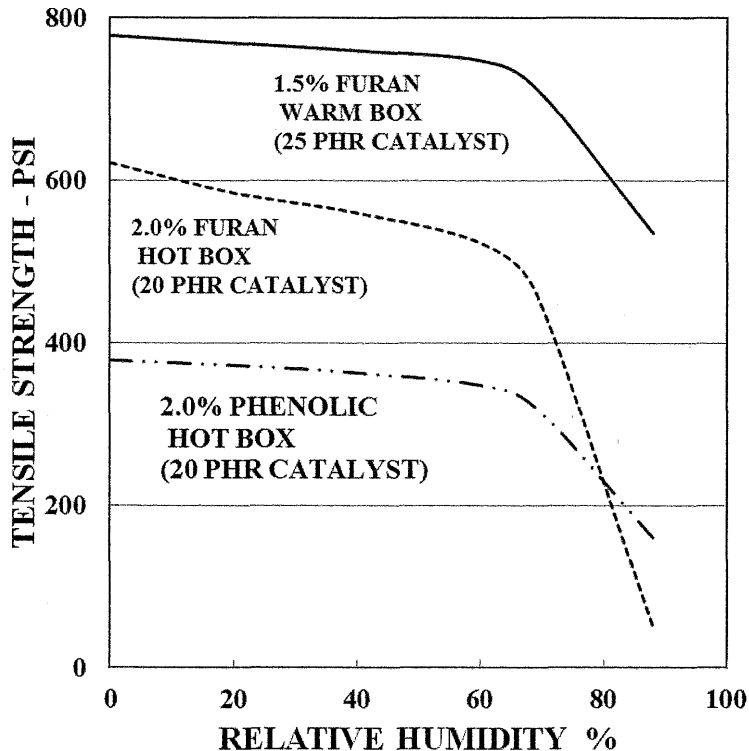6. Short cycle time with no post curing.

FIGURE 3.72   Resistance to humidity of several binders. (From Carey [54, 59].)

The major disadvantage is the relatively high cost, 2 to 3 times for the resin and 3 to 7 for the catalyst compared to the hot box. However, if the Shell Process produces a solid core because of the design, then warm box may be justified.

Gas-Cured Binder Systems

Over the years several resins have been developed that allow cores and molds to be used immediately after production and cleaning. For example, a gaseous amine can be used with the original phenolic urethane resins rather than a Part III that contains a solution of an amine. The advantage is that any weight of sand can be cured almost instantly, with excellent dimensional accuracy and stability of molds or cores and lower labor and energy costs. The disadvantages are that the amine has to be heated slightly to vaporize it, mixed with air, and as the amine has a strong odor, the core or mold has to be flushed to remove excess amine and the gases chemically cleaned. The process requires a vaporizer and scrubber system. Core blowers or shooters are the most common production method with PUCB (phenolic urethane cold box) sand mixes. Core boxes can be top blow, edge blow, vertically or horizontally split, and filled at pressures of 35 to 45 psi [54, 60, 65].

Although almost any material can be used for construction of core boxes, iron holds up the best as it resists release agents, cleaning solvents, scratching, gouging, and erosion from the sand. A variety of different vents can be used, but the preferred type is a wire screen mesh of 25 to 30 mesh to retain the sand, while passing the most gas. The combined area of all exit vents should be 70% of those of the input blow tubes. Strategic placement of vents is necessary for the catalyst gases to pass through all sections, and most importantly to achieve a uniform cured sand permeability.

The CO_2 process has been modified in 1968, with the addition of an ester to the water glass. This binder allows additives to improve shelf life, and minimizes casting defects while offering superior surface finish. Carbon dioxide only needs good ventilation and no nearby pits to collect in. A CO_2-cured alkaline phenolic cold box binder is also available that can be hand-cured or blown.

There have been a number of SO_2 processes, the first, or Sapic Process in 1975, had a number of issues [60, 65]. It was later modified to consist of an epoxy resin and a peroxide. The current system uses two resins, an epoxy (as in the adhesive) and an acrylic (the ingredient in a shatterproof clear plastic that can substitute for glass). This binder system has the highest strength, the longest mixed bench life and the best casting properties. The two resins can be mixed in different proportions to tailor core making, handling, and casting properties. Part A is an epoxy resin with an organic hydroperoxide. Part B contains acrylic resin, epoxy resin, additives, and solvents if necessary. Upon exposure to SO_2, the acrylic cures rapidly by a free radical mechanism with the SO_2 acting as a catalyst. This gives the system early handling strength. The epoxy cures as it absorbs the SO_2, and the two react with the SO_2 to become a solid mass. The epoxy reacts slowly enough to get a good release and ultimately high hot strength. Binder levels are from 0.5 to 2%. High hot strength formulations are used for iron and steel which avoid veining and erosion type defects. Aluminum foundries require a formulation with better shakeout characteristics. Generally, SO_2/N_2 mixtures are used as this lowers the amount of SO_2 used and facilitates purging the SO_2 left in the core. The flushed gases have to be scrubbed. The used sand can be reclaimed mechanically, although many prefer thermal reclamation as it lowers the LOI, but requires removal of SO_2 from off-gases of reclaimers.

Table 3.26 shows a brief comparison of the performance of some of the organic binder systems. This concludes the section on organic binders. Only some of the more

Process	Binder Level	Tensile in psi after 5 Minutes	Cure Time 20 lb or 10 kg Core	Bench life at 90°F (32°C)	Shelf Life of Resins	Moisture Resistance
CO_2-cured alkaline phenolic	3.0%	65	75 s	1–2 h	6 mo	Good
Phenolic urethane	1.3%	150	5–10 s	1–2 h	>1 y	Good
Methyl formate alkaline phenolic	1.75%	94	10–15 s	2–3 h	3 mo	Good
Acrylic-epoxy SO_2	1.1%	140	5–10 s	Weeks	>1 y	Good
Silicate-CO_2	3.5%	43	75 s	1–2 h	>1 y	Poor

Source: Carey [54], Carey and Sturtz [60].

TABLE 3.26   Performance Properties of Common Cold Box Systems

popular systems have been covered due to space limitations. However, most of the techniques and operating issues that occur with some systems occur in others. There are still foundries using core oils for a few special jobs, however, the reader is referred to the Second Edition of Dietert or Carey [54, 60, 65 (AFS), 68].

Inorganic Binders

The principal types of inorganic binders (other than clay) are silicates, phosphates, and cement.

CO_2 Process

Although the CO_2 process was discovered in 1898, silicates have only been used in foundries since 1947, and originally as a heat-cured binder [60, 65]. The cold-box CO_2-silicate (gas-cured) system was introduced in 1968. This nobake silicate binder uses organic esters, an aqueous solution of sodium silicate, and CO_2 gas. There are no environmental or waste disposal issues. The binder is odorless, nonflammable, and can be used with all sand aggregates to make molds and cores. No noxious gases and minimal emissions are released during pouring, cooling, or at shakeout and although a considerable volume of gases are liberated, the main ingredient is steam.

Chemical companies supply liquid sodium silicates with varying proportions of silica and sodium oxide with a wide range of viscosities because properties vary with the silica (SiO_2): soda(Na_2O) ratio. Typical viscosities are between 48 and 52 Baumé (Be) and silica soda ratios (SiO_2:Na_2O) between 2.0 and 2.8 to 1. Ratios of 1.9 to 3.2 are used in other applications. Sodium silicate formulations with a wide range of chemical and physical properties can be made by controlling the ratio and water content. The curing process involves two mechanisms [Eq. (3.13)]. In the first reaction, sodium metasilicate, Na_2SiO_3, reacts with CO_2 gas to form sodium carbonate and silica gel. At this stage, the system has reached 20 to 40% of its ultimate strength. The second mechanism is the dehydration of the silica gel to form a glass-like bond [69].

$$Na_2SiO_3 + 2H_2O + CO_2 \rightarrow Na_2CO_3 + Si(OH)_4 \rightarrow SiO_2 \qquad (3.13)$$
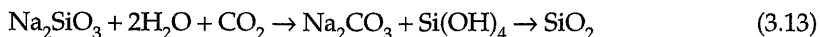
Sodium silicate-sand mixes can be made by batch or continuous mixers. Continuous mixers need only a single pump to meter the correct amount of binder. Overmixing reduces the bench life of the sand mixture. Mixes have a bench life of up to a week

(longer in a plastic bag), although higher silicate ratios shorten the life. Hoppers of mixed sand should be covered with plastic sheets or damp sacking to prevent premature hardening (crusting).

The binder level for cores and molds varies from 3 to 6% depending on the type of sand, grain fineness, and sand purity. Additional factors are the nature of the metal, the pouring temperature, and the required erosion resistance. A washed-and-dried, rounded, silica sand grain (AFS GFN 55) requires approximately 2.5 to 3% of binder. Finer sands (AFS GFN 120-140) require from 1.5 to 3% more binder. It is recommended that test cores with an average amount of binder be used when determining the amount of binder for a specific job. Initial tensile strength of cores gassed for 5 seconds with CO_2 vary from 37 to 45 psi (2.6 to 3.2 kg/cm^2) depending on the binder level. The strength increases to a maximum of 100 to 200 psi (7 to 14 kg/cm^2) after 24 hours at room temperature, partly from some dehydration of unreacted silicates and the continued gelling of the silicate. However, high humidity in the first 24 hours can reduce dehydration and strength development. Formulations containing organic additives such as sugars, starches, or carbohydrates are particularly susceptible to high humidity; and a short heating cycle is needed. When a core is hardened by carefully controlled gassing and further hardened by dehydration and polymerization during the subsequent 24 hours, good strengths are maintained over a long period of storage. It is always better to date sodium-silicate-bonded/CO_2-hardened cores, so that the oldest cores are used first.

A CO_2 system should supply approximately 1 to 2 lb of carbon dioxide (8.5 to 17 ft^3) for every 100 lb of silicate-coated sand (1 to 2 kg per 100 kg of sand or 0.53 to 1.1 m^3). In addition, the process requires a CO_2 regulator, flow meter, and timer for success and uniformity. Probes, hoods, or cups are used for gassing. Gassing with CO_2 must be done carefully as overgassing and undergassing adversely affect properties. Fiberglass tubing and lanced vents are used to distribute CO_2 to all parts of the mold. Nevertheless, there is always a tendency to overgas some parts of the core or mold to ensure that all parts are cured. The gassing operation is more critical with the higher ratio binder, as shorter gassing times are needed, they are easily overgassed, and shelf life shortened. Overgassing produces bicarbonate which is evident as white crystals on the mold surface. The following general rules apply to all gassing techniques:

1. Gassing times needed for strength development are proportional to the binder level.

2. Longer gassing times at moderate flow and pressure are superior to shorter times at higher pressures for strength development.

3. Lower silicate ratios require more CO_2 and the cores have poorer collapsibility.

4. CO_2 pressure is 20 to 60 psi (1.4 to 4.2 kg/cm^2); but 30 to 40 psig (2 to 3 kg/cm^2) works best.

5. The hardening rate is temperature-sensitive and very slow below 50°F (10°C).

Small cores and molds can be successfully produced by combining core blowers or core shooters with programmed gassing stations operating on predetermined cycles. Higher production rates are possible with two core boxes; while one box is being gassed, the other can be filled. Carbon dioxide can be injected through (1) a hollow pattern or double-walled core box, (2) a hood covering the box, or (3) a mandrel into a core. Larger cores can be cured with $\frac{3}{16}$ in (5 mm) diameter lance pipes. Holes are punched with a rod approximately 6 in (15 cm) apart. The lance is then successively inserted into each

hole and the gas applied for 10 to 15 seconds. The gas will permeate and cure a section of sand about 3 in (7.5 cm) around the hole. Large cores and molds are easily gassed with a full gasket designed to cover the flask or box.

Core boxes and patterns can be wood, metal, or plastic. With the exception of wood, they should be washed and metal core box tooling can be soaked overnight. This soaking treatment simplifies cleaning blow vents. Slotted screen vents are very effective when using sodium silicate core-box tooling, but are easily damaged during removal of the hardened and encrusted sand mixture.

A Japanese variant of the process uses less binder. The packed flask is moved over a rubber pad, a chamber lowered on to it, and the chamber evacuated before introducing the CO_2 gas into the chamber. This avoids overgassing, considerably reduces the gassing time and the need for ducts and holes. The Japanese process not only uses 40% less binder, but the sand can be mechanically reclaimed for reuse in the process. The conventional process introduces higher levels of sodium, which would poison the cure with rebonded sand [70].

Sometimes additives are necessary and vital to the success of the casting. Additives such as sugars are used to improve shakeout or collapsibility. They are sold with the silicate binder, but can be added separately to a sand mixture. However, reducing the binder level or using a higher ratio silicate can improve shakeout. The use of additives in the silicate mold and core mixtures will not remedy poor formulations or faulty procedures. Additives seriously lower bond strengths, but additives are recommended to

1. Improve collapsibility
2. Control expansion
3. Prevent burn-on/burn-in and metal penetration
4. Promote peel of castings and improving casting finish
5. Improve flowability of the sand mixture
6. Create the proper mold atmosphere
7. Prevent excessive drying of the sand mixture
8. Prevent sticking of sand mixture to patterns and core boxes

Iron oxide, plumbago, and polymers are added to silicate-bonded sands for copper-base alloys.

Phosphate Self-Setting Binder

Phosphate binder systems consist of liquid mixtures of monoaluminum phosphate and orthophosphoric acid which are hardened by reacting with an addition of magnesium oxide (modified with zinc in Part A or B). This inorganic binder was developed by Ashland (known as ASK since 1993) as an alternative to sodium silicate and the demand for more environmentally friendly systems [65, 71].

Recommended binder levels are 2.5 to 3.0% for molds and 3.5 to 4.0% for cores. The amount of powdered Part B oxide is from 18 to 35% of the binder mix, depending on sand temperature and impurities, mixing efficiency, and the desired work life. The powder should be added by positive-type conveyors. If a continuous mixer is used the blade angles should be adjusted to improve mixing time (reduced to 2/3 of rated capacity). Varying the Part B from 18 to 35% [of a total 3.5% binder (BOS)] causes the work time to go from 18 to 2 minutes and the strip time from 65 to 8 minutes at 75°F (24°C). The reaction is strongly