

# CONCRETE TECHNOLOGY *Today*

## Chicago Building Bridge to the Future

by Martin McGovern



*Workers from Walsh Construction Inc. place concrete for the elevated deck. (69927)*

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## High-performance concrete is the centerpiece in reconstruction of historic Wacker Drive

Wacker Drive, an L-shaped stretch of bi-level roadway that runs through the heart of downtown Chicago, is currently undergoing a \$200 million reconstruction of most of its 2.4-km (1.5-mile) length.

Determined to build maximum longevity into this heavily traveled thoroughfare, the city has set an ambitious goal: a 75- to 100-year design life. The material of choice? High-performance concrete.

The concrete for the columns and the 330-mm (13-in.) thick, post-tensioned elevated deck contains 311 kg/m<sup>3</sup> (525 lb/yd<sup>3</sup>) of portland cement, as well as 10% (by mass of cement) Class F fly ash, 5% silica fume, and 15% ground granulated blast-furnace slag (see box on next page). The mix was developed by Wiss, Janney, Elstner Associates Inc. (WJE) and the University of Illinois-Chicago.

### Stronger Not Always Better

According to Paul Krauss, senior consultant with WJE, the mix was designed with the goal of maximizing durability, not compressive strength. In fact, a limit of 65.5 MPa (9,500 psi) was placed on the 28-day compressive strength of the concrete to avoid creating an overly rigid structure. "Excessively high

## Wacker Drive Reconstruction, Chicago High-Performance Concrete

### Mix Proportions

Material	Quantity	
Portland cement (Type I)*	311 kg/m <sup>3</sup>	(525 lb/yd <sup>3</sup> )
Fly ash (Class F)	31 kg/m <sup>3</sup>	(53 lb/yd <sup>3</sup> )
Silica fume (dry)	16 kg/m <sup>3</sup>	(27 lb/yd <sup>3</sup> )
GGBFS** (Grade 100)	47 kg/m <sup>3</sup>	(79 lb/yd <sup>3</sup> )
Fine aggregate	676 kg/m <sup>3</sup>	(1,140 lb/yd <sup>3</sup> )
Coarse aggregate	1,068 kg/m <sup>3</sup>	(1,800 lb/yd <sup>3</sup> )
Water†	150.8 kg/m <sup>3</sup>	(254 lb/yd <sup>3</sup> )
Water Reducer (Type A)	1.6 L/m <sup>3</sup>	(41 oz/yd <sup>3</sup> )
HRWR (Type F)	2.1 L/m <sup>3</sup>	(55 oz/yd <sup>3</sup> )
AE Admixture	as needed to achieve 7% ± 1 1/2 % air content	

\* Equivalent alkalies (Na<sub>2</sub>O + 0.658 K<sub>2</sub>O) <0.60%

\*\*Ground granulated blast-furnace slag

† Water-cement ratio = 0.36 to 0.38

### Performance Requirements

Property	Requirement	Test Method
Slump after HRWR addition (max)	200 mm (8 in.)	AASHTO T 119 (ASTM C 143)
Slump after 45 minutes (min)	100 mm (4 in.)	AASHTO T 119 (ASTM C 143)
Initial set time (min)	3 hr	AASHTO T 197 (ASTM C 403)
Total air content, plastic concrete	7% ± 1 1/2%	AASHTO T 152 (ASTM C 231)
Total air content, hardened concrete	7% ± 1 1/2%	ASTM C 457
Air void spacing factor (max)	0.25 mm (0.010 in.)	ASTM C 457
Air void specific surface (min)	12,500 mm <sup>2</sup> (500 in. <sup>2</sup> )	ASTM C 457
Compressive strength, 28 days (min)	41.4 MPa (6,000 psi)	AASHTO T 22 (ASTM C 39)
Compressive strength, 28 days (max)	65.5 MPa (9,500 psi)	AASHTO T 22 (ASTM C 39)
Freeze-thaw resistance	DF>90% at 300 cycles DF>85% at 500 cycles	AASHTO T 161 (ASTM C 666)
Chloride permeability (28 days)	<2,000 coulombs	AASHTO T 277 (ASTM C 1202)
Chloride penetration	13–25 mm (1/2–1 in.), <0.03% Cl <sup>-</sup> by mass of concrete at 90 days 13–25 mm (1/2–1 in.), <0.07% Cl <sup>-</sup> by mass of concrete at 6 mo.	AASHTO T259/T260
Salt scaling resistance	Rating of 0–1 at 50 cycles	ASTM C 672
Drying shrinkage	<600 x 10 <sup>-6</sup> at 90 days	AASHTO T 160 (ASTM C 157)

To minimize penetration of deicing salts applied during the harsh Chicago winters, the concrete has to meet strict requirements for chloride permeability. According to Krauss, the proportions of fly ash, silica fume, and GGBFS were chosen to minimize permeability while avoiding potential negative side effects. The silica fume content is limited to 5% to avoid a high water demand, and the fly ash dosage is limited to 10% to reduce the impact of possible variations in chemical composition.

The air content of the concrete (7% ± 1 1/2%) is also meticulously controlled to ensure adequate freeze-thaw durability. Each truckload is checked at a testing station at the jobsite and periodically after the concrete exits the pump. Concrete specimens cast at the jobsite each month are also checked for air content in the hardened concrete.

### Supplier Meets Challenges

Because the concrete loses about 1 1/2% to 2% air during pumping, concrete supplier Prairie Materials sends batches to the job with an air content of 9% to 10%. Although the project called for the superplasticizer to be added at the jobsite, Prairie found that by adding about one-third of it at the plant, they could more easily control the air content. "The added workability of the concrete allowed the air entrainer to fully activate, which reduced air content variability," says Gary Hall, quality control technician at Prairie.

### Post-Tensioning Provides Benefits

The upper deck of Wacker Drive is being constructed as a two-way, bonded post-tensioned elevated slab. A post-tensioned deck was chosen for two reasons. First, the compressive stress induced by post-tensioning minimizes cracking and crack widths. Second, the lower level of Wacker Drive required an increase in vertical clearance. However, the road could be lowered only 75 mm (3 in.) without affecting utility lines running beneath it. Post-tensioning allowed the overall thickness of the upper deck to be reduced from 610 to 380 mm (24 to 15 in.), resulting in a 305-mm (12-in.) increase in vertical clearance for the lower level.

The deck has 50 mm (2 in.) of concrete cover over epoxy-coated reinforcement. After the high-performance concrete deck is placed, a 57-mm (2.25-in.) thick, latex-modified bonded overlay is placed for additional protection.

compressive strengths produce a concrete with high modulus and low creep, which can lead to cracking when the deck tries to move due to thermal changes or shrinkage," says Krauss.

Keeping the cementitious materials content (405 kg/m<sup>3</sup>, 684 lb/yd<sup>3</sup>) and the water-cementitious materials ratio (0.36 to 0.38) at reasonable levels also provides constructibility benefits as well. "This mix is easier to place and finish than a mix with an excessive amount of cementitious materials and a very low water content," says Krauss. "It's more forgiving in the field."

# Cement Specification Emphasizes Performance

by Paul D. Tennis

## ASTM C 1157, covering both blended and portland cements, moves away from requirements on chemical composition

ASTM C 1157, *Standard Performance Specification for Hydraulic Cement*, is a relatively new specification in which restrictions on composition of the material are minimized. For the producer, ASTM C 1157 allows optimal use of raw materials and the ability to produce innovative cements. For the specifier, it contains optional requirements that are not available under other specifications. Requirements in C 1157 are largely based on C 150 and C 595, the traditional, cement specifications that contain a combination of prescriptive and performance limits. However, the newer specification contains unique features as well.

ASTM C 1157 was first approved in 1992 as a performance specification for blended cements; however, in 1998 it was amended to include portland cements. Thus, for the first time, both portland and blended cements could be specified under one standard based on identical performance requirements. Cements are classified into six types according to their intended use: GU for general construction, HE for high-early strength, MS for moderate sulfate resistance, HS for high sulfate resistance, MH for moderate heat generation, and LH for low heat generation. An optional suffix, R, may be added to the cement type (for example, GU-R) if laboratory testing (C 227) indicates the cement is resistant to alkali-silica reactivity (ASR).

### Focus On Performance

The new specification represents a shift away from prescriptive specifications that dictate composition restrictions. Instead, the emphasis is on the ability of the cement to perform. For example, in C 150, the tricalcium aluminate ( $C_3A$ ) content in Type II or V cement is prescriptively limited to control sulfate resistance. In ASTM C 1157, assurance of sulfate resistance of Type MS or HS cement is determined by testing (C 1012) mortar bars made with the cement. The laboratory test, rather than a chemical analysis, is used as a predictor of performance.

**Table 1. Default Minimum Strength Requirements of ASTM C 1157 (ASTM C 109), MPa (psi)**

	Cement Type					
	GU	HE	MS	HS	MH	LH
1 day		10 (1450)				
3 days	10 (1450)	17 (2465)	10 (1450)	5 (725)	5 (725)	
7 days	17 (2465)		17 (2465)	10 (1450)	10 (1450)	5 (725)
28 days				17 (2465)		17 (2465)



Many limits in C 1157 applicable to all cement types are similar to requirements in C 150 and C 595. All cement types in C 1157 are required to meet maximum autoclave expansion (0.8%) and maximum mortar bar expansion (0.020% at 14 days) limits that are identical to those in C 150 and C 595. Likewise, initial setting time (Vicat test, C 191) is between 45 and 420 minutes, which is identical to C 595 and only slightly extended from C 150 (between 45 and 375 minutes). One optional requirement, that for early stiffening (C 451), is identical to an optional requirement in C 150. Unlike C 150 and C 595, C 1157 does not include requirements for air-entraining cement. Air content (C 185) and fineness (C 204) are reported for informational purposes, but have no specification limits.

### Unique Strength Provisions

The strength provisions of C 1157 are an example of one of the unique aspects of the specification. By default, strength requirements are the minimums shown in Table 1. However, there are several optional requirements that can be invoked by the specifier, including an optional 28-day strength requirement, alternative (higher) minimums at specific ages, and strength ranges (within maximum and minimum values) applied at a specific age. Thus, if a specifier has an application requiring cement within a particular range of strengths, C 1157 provides an opportunity for invoking specific optional requirements to address that need. However, specifiers should be aware that cements may not be available to meet

*continued to page 4*



*continued from page 3*

optional requirements and should check with their cement or concrete supplier to determine whether particular options are available in their area.

For sulfate-resistant and controlled-heat-of-hydration cements, requirements are based on performance tests with limits again similar to those in C 150 and C 595. For example, Type MH cements are required to generate (C 186) less than 290 kJ/kg at 7 days, matching optional requirements for low heat Type II in C 150 and the MH option in C 595. Type LH cements are required to generate less than 250 kJ/kg at 7 days and less than 290 kJ/kg at 28 days, identical to the requirement for equivalent types in C 150 (Type IV) and C 595 (LH option). Requirements for Type MS cements, maximum expansion (C 1012) of 0.10% at 180 days, are similar to optional requirements in C 150 for Type II and for

optional sulfate-resistant cement in C 595. Type HS cements have more restrictive requirements based on C 1012: 0.05% at 6 months, or 0.10% at 1 year.

In summary, many ASTM C 1157 performance requirements are similar to those in the more traditional C 150 and C 595 specifications. However, options for specifying cements with particular properties that cannot be specified elsewhere are also included. This brief review cannot cover all provisions of the standard; readers are encouraged to carefully examine the specification for complete details. ASTM C 1157 can be ordered from ASTM's Web site at [www.astm.org](http://www.astm.org), or by calling 610.832.9585.



## Technology Q & A

### Does magnesium chloride harm concrete?

**Q.** Our state recently began using magnesium chloride as a road deicer, and we've noticed an increase in the scaling of concrete. Does magnesium chloride cause more damage to concrete than conventional road salt (sodium chloride)?

**A.** A PCA literature search found three references comparing the effects of magnesium chloride with sodium chloride and other deicers on the scaling resistance of concrete. Unfortunately, the cited studies provide conflicting results.

The abstract from a German field study (Leiser 1967) states that "concrete surfaces were only slightly affected [by magnesium chloride lye], and that the solution is less harmful than granulated salt."

However, two recent studies found magnesium chloride to be more aggressive than sodium chloride. In the first study (Cody 1996), concrete containing dolomite coarse aggregate was cored from five highway pavements. Small blocks were cut from the cores and subjected to wet-dry and freeze-thaw cycles in 0.75M and 3.0M solutions of NaCl, CaCl<sub>2</sub>, and MgCl<sub>2</sub>. Magnesium chloride was the most destructive deicer, producing severe deterioration under almost all of the experimental conditions. Calcium chloride was the next most destructive salt. Sodium chloride was relatively benign.

In the second study (Lee 2000), the researchers again found magnesium chloride to be significantly more aggressive than sodium chloride in wet-dry and freeze-thaw conditions.

In both of these studies, the authors concluded that the major cause of deterioration by magnesium-based deicers was the formation of non-cohesive magnesium silicate hydrates (MSH), produced by the reaction of dissolved magnesium with calcium silicate hydrates of the cement. Because MSH does not form strong bonds with aggregate particles, these phases cause loss of cohesion in portland cement paste and will promote crumbling.



A common finding of the above research is that all deicers can aggravate scaling, emphasizing the need for placing high-quality, air-entrained concrete in deicer environments.

### References

Cody, R.D., Cody, A.M., Spry, P.G., and Gan, G., "Experimental Deterioration of Highway Concrete by Chloride Deicing Salts," *Environmental & Engineering Geoscience*, Vol. II, No. 4, Winter 1996, pp. 575-588.

Lee, H., Cody, R.D., Cody, A.M., and Spry, P.G., "Effects of Various Deicing Chemicals on Pavement Concrete Deterioration," *Proceedings of the Mid-Continent Transportation Symposium*, Center for Transportation Research and Education, Iowa State University, 2000.

Leiser, K., and Dombrowski, G., "Research Work on Magnesium Chloride Solution Used in Winter Service on Roads," *Strasse*, Vol. 7, No. 5, Berlin, Germany, May 1967.



# Freeze-Thaw Durability of High-Strength Concrete

## High-strength concrete has low permeability. So how much entrained air is needed to make it frost resistant?

That is the question Dr. Pinto and Dr. Hover of Cornell University address in a recently released 75-page report, *Frost and Scaling Resistance of High-Strength Concrete*. In this laboratory study, researchers tested 18 concrete mixtures with six different water-to-cement ratios (0.50, 0.45, 0.35, 0.40, 0.30, and 0.25) and three different air contents (non-air-entrained, 4%, and 6%). Surface finishing of the specimens was initiated at two different times relative to the time of initial set as defined by ASTM C 403.

The frost resistance of the concrete was measured in two ways. ASTM C 666 was performed using resonant frequency to assess damage in the core or "bulk" of the specimens. ASTM C 672 was performed to evaluate the scaling resistance of the concrete surface.

The report compares the results of the study to the current recommendations of ACI 318-99, *Building Code Requirements for Structural Concrete*. ACI 318-99 sets air content requirements for all concrete exposed to freezing and thawing while wet, with a tolerance of  $\pm 1\frac{1}{2}\%$  (see table). The code permits reducing these values by 1% when the specified compressive strength of the concrete is greater than 35 MPa (5000 psi). In addition, ACI 318-99 requires a maximum water-to-cementitious materials ratio (w/cm) of 0.45 by mass for concrete to be exposed to freezing and thawing in a moist condition or subjected to deicing chemicals.

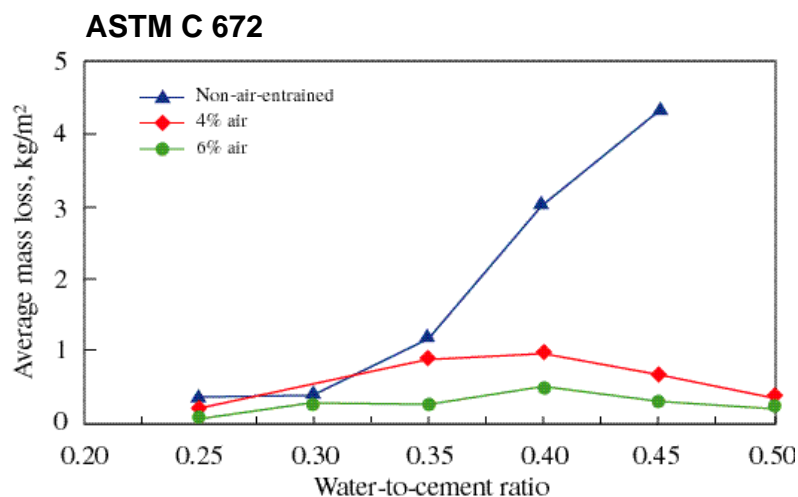


Fig. 1. Effects of air content and water-to-cement ratio on scaling resistance of portland cement concrete.

## ACI 318-99 Requirements for Total Air Content for Frost-Resistant Concrete (Severe Exposure)

Nominal maximum aggregate size, mm (in.)	Air content, %*
9.5 ( $\frac{3}{8}$ )	7.5
12.5 ( $\frac{1}{2}$ )	7.0
19.0 ( $\frac{3}{4}$ )	6.0
25.0 (1)	6.0
37.5 ( $1\frac{1}{2}$ )	5.5

\* Tolerance of  $\pm 1.5\%$  allowed. For concrete with compressive strength  $>35$  MPa (5000 psi), a reduction of 1% is allowed.

## Selected Results

The results of the research suggest that ACI 318 requirements for total air content are conservative. Were it not for the 1.5% tolerance, only three mixtures from the entire study would have met the air requirements for severe exposure, even though all but three mixtures performed well in ASTM C 666 testing.

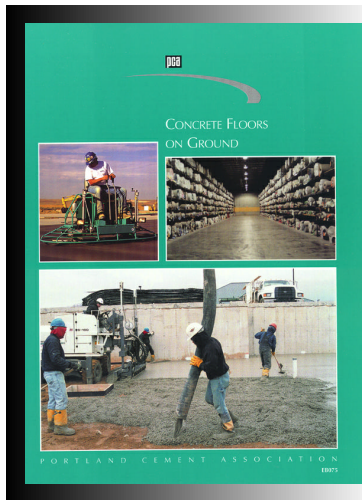
The researchers also stated that the ACI 318 requirement that the water-to-cement ratio be less than or equal to 0.45 for frost resistance is conservative. They found that air-entrained mixtures with a water-to-cement ratio of 0.50 were frost and scale resistant. Other results showed that air entrainment is not necessary for mixtures with a water-to-cement ratio of 0.25 (Figure 1). When scaling resistance is not required, air entrainment may not be necessary for mixtures with a water-to-cement ratio less than 0.35.

These observations apply to concrete that is wet cured and incorporates only portland cement, water, frost-resistant aggregates, and chemical admixtures. ACI 318 air content limits apply to concretes with and without supplementary cementitious materials, such as fly ash and silica fume. These findings may therefore not apply to mixtures incorporating such materials.

Editor's Note: To order a copy of RD122, *Frost and Scaling Resistance of High-Strength Concrete*, call 800.868.6733 or visit the PCA Web site at [www.portcement.org](http://www.portcement.org), select the Online Catalog, and enter "RD122" in the search field.

## Floor Construction, A to Z

### Expanded and updated book provides detailed information on constructing slabs on ground, from subgrade preparation to toppings and finishes



Over the past decade, floor construction has become more complex as owners and designers have demanded better performance and reduced maintenance from floor systems.

These changes are reflected in the 2001 edition of PCA's popular book, *Concrete Floors on Ground* (EB075), which has been updated and greatly expanded to 148 pages from the previous 40-page edition. With its practical focus, extensive photographs, and numerous tables and charts, this easy-to-understand publication serves as a design guide, construction manual, and authoritative reference.

After outlining the proper methods for subgrade and subbase preparation, the book discusses moisture control, including when and how to use vapor retarders. The chapter on concrete materials includes the recommended compressive strength and slump of concrete for different types of floor traffic and surface finishes. It also discusses the properties of fresh and hardened concrete that affect floor durability. Designers will appreciate the chapter on floor thickness design, which covers flexural stresses and safety factors for vehicle loads, post loads, and distributed loads.

Crack control, an important aspect of floor construction, is covered with discussions of proper joint spacing and layout, load transfer, and the benefits of distributed steel. Another chapter covers the proper methods of concrete placement and finishing and how the timing of these tasks affects surface finish. It also lists the finishing methods needed to produce floors that meet various flatness and levelness tolerances.

Floors exposed to heavy traffic often require a topping or special finish to increase their wear resistance. Some of the options described are dry-shake hardeners, bonded toppings, and liquid floor hardeners.

Moisture vapor transmission has a significant impact on the durability of floor coverings, such as adhered tile and impermeable coatings. The book covers the sources of moisture vapor transmission and methods of measuring the transmission rate.

Proper maintenance can extend the life of concrete floors, and the book summarizes the types of defects and deterioration that can occur on floor slabs and describes methods for preventing and repairing many common cosmetic and structural problems.

The last chapter is devoted to floors with special technical or aesthetic needs. These include white cement concrete floors, radiant-heated floors, and colored and textured floors.

To obtain a copy of *Concrete Floors on Ground* (EB075), call PCA at 800.868.6733 or visit the PCA Web site at [www.portcement.org/floors](http://www.portcement.org/floors).



## Slag Cement Association Formed

Formed in early 2001, the Slag Cement Association (SCA) promotes the increased use of slag cement and portland-slag cement blends. Slag is produced during the reduction of iron ore to iron. Molten non-iron minerals are separated, rapidly quenched, then ground to a fine powder, called slag cement.

Association membership is composed of seven companies: Essroc Cement Corp., Holnam Inc., Lafarge/Blue Circle Inc., Lafarge North America Inc., Lehigh Portland Cement Co., Lone Star Industries Inc., and St. Lawrence Cement Co. These firms account for the majority of slag cement shipments in the United States.

The Slag Cement Association's Board of Directors recently named Jan R. Prusinski, P.E., as its Executive Director. Prusinski was formerly the Portland Cement Association's Program Manager for Soil-Cement and Roller-Compacted Concrete Pavements. He holds a B.S. in Civil Engineering from the University of Michigan, and an M.B.A. from the University of Houston.

For more information, contact SCA, P. O. Box 2615, Sugar Land, TX 77487-2615, 281.494.0782 (phone), 281.494.0784 (fax).



## New Information Products

The following information products are now available. To purchase them in the United States, contact the Portland Cement Association, Customer Service, P.O. Box 726, Skokie, IL 60076-0726; telephone: 800-868-6733, fax: 847.966.9666, or Web site: [www.portcement.org](http://www.portcement.org) (fax and Web available 24 hours/7 days a week). In Canada, please direct requests to the nearest regional office of the Cement Association of Canada (Halifax, Montreal, Toronto, and Vancouver).

### Concrete Slab Surface Defects: Causes, Prevention, Repair, IS177

Are you tired of callbacks concerning the condition and appearance of floors and other flatwork? This new 2001 edition describes the causes, prevention, and repair of 10 common concrete slab surface defects: dusting, scaling, popouts, crazing, cracking, discoloration, blisters, spalling, low spots, and curling. Describes how petrographic (microscopical) analysis can be used to determine the cause of most concrete defects.



### Troubleshooting and Repair of Concrete, CD027

Created around the U.S. Army Corps of Engineers' *Evaluation and Repair of Concrete Structures*, this CD provides a compact and easy-access guide to the troubleshooting and repair of concrete. The CD uses the original information from the Corps' document, along with updated photographs and a user-friendly navigation and search system that makes the document come alive. The CD also contains a state-of-the-art search capability for terminology and a history section that allows users to identify the sections they visited.

### Top 10 Myths in Concrete Construction, VC128

Is stronger concrete always better? Does curing concrete mean letting it "dry?" Get a candid look at 10 popular, but mistaken, myths that exist in concrete construction. Use this video to properly train new employees, or as a reality check for experienced personnel. Provides point-by-point discussion of the facts to do the job right the first time.

### Compilation of Concrete Reports, RX500

This compilation of over 200 of PCA's primary technical reports is a quick and economical way to build your concrete technology library. An ideal reference for technical service professionals responding to customer needs, the reports contain authoritative information on concrete technology, cement performance, structural design, environmental issues, durability, special concretes, and concrete ingredients from admixtures to slag. Applications range from buildings to pavements. Includes available past issues of *Concrete Technology Today* and *Masonry Today*. After receiving the paper compilation, you can use the PCA Web catalog to search specific topics at [www.portcement.org](http://www.portcement.org). Only original documents are provided while supply lasts. The series is not continuous, as many items are no longer in print.





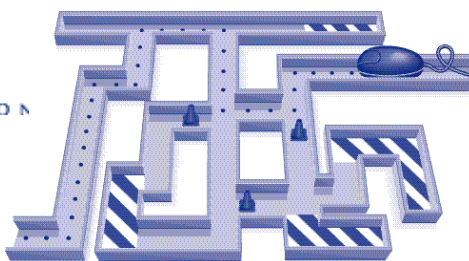
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