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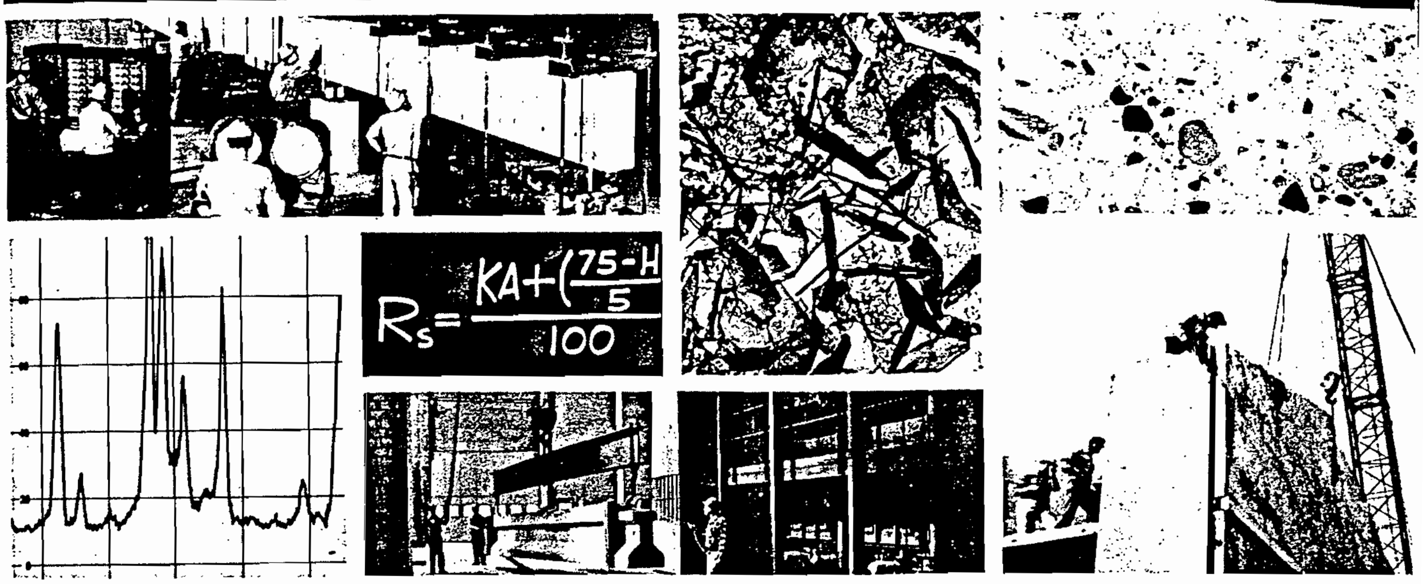

Specifications and Selection of Materials for Masonry Mortars and Grouts

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SYNOPSIS

Mortar and grout specifications are reviewed and correlated with the construction and performance requirements of masonry. The roles of mortar and grout are explained in terms of the development of the individual plastic and hardened properties, commencing with materials selection. Some nonspecified physical properties are shown to be of equal or greater significance to masonry performance than those currently specified. Field testing and all-weather considerations are included in the discussion.

The author concludes that existing specifications are adequate for pre-construction evaluation of the materials of construction. However, existing specifications must be extended to include additional pre-construction and construction-site tests with appropriate limits. Attainment of these objectives will allow perfecting mortar and grout recommendations for masonry construction.

Keywords: admixtures, aggregates, air entrainment, bonding, cements, compressive strength, durability, field tests, grout, masonry, moisture content, mortar (materials), relative humidity, specification.

INTRODUCTION

Much has already been written about the role of masonry mortars and grouts in masonry construction. Masonry is or can be a versatile composite because the possible combinations of masonry units, mortars, grout, and design are unlimited. For originality this versatility is desirable; however, change requires decisions. In this case, the major decision involves selection of the right materials to produce a durable structure with the desired performance characteristics.

Mortars for masonry construction are the mixtures used to join the individual construction materials, be they brick, concrete masonry, or glass. To join the individual units effectively, the mortar must possess: excellent adhesion at the masonry unit-to-mortar interface; adequate tensile and compressive strength, individually and combined as shear resistance to withstand imposed loads; sufficient density to provide watertightness; and ample extensibility to accommodate movements caused by moisture and temperature changes or building settlement. For reinforced masonry, mortars of higher cement content are required, whereas mortars of moderate to high cement content are required for plain masonry.

Grouts for masonry construction are the mixtures used to join the individual masonry units with metal reinforcement. The coupling of these construction materials within masonry balances tensile and compressive strengths and increases the masonry's ability to resist imposed loads.

Both of these mixtures, mortars and grouts, are quite similar in their composition and, consequently, one might anticipate that their performance characteristics are equally similar. However, their performance characteristics differ because the two mixtures are subjected to different exposure conditions during the early minutes, hours, and days after construction. From the first contact of mortar or grout with the masonry unit, the fresh plastic mixture is rapidly transformed into a rigid mass capable of supporting loads. These changes that transpire and an understanding of outside influences are considered of primary importance for proper selection and construction of durable masonry.

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MORTARS

The role of the mortar in construction is to join the individual units together, yielding masonry with the desired performance characteristics. To satisfy the architect-engineer team, the mortar must possess: the desired compressive, shear, and tensile strengths; resistance to air and water penetration; bond of mortar to masonry units and to steel in joints; and the esthetic blend or contrast of unit with joint. In addition, to satisfy the masonry contractor and mason, the mortar must possess workability that will allow production of quality masonry.

To produce masonry with the desired performance characteristics, considerable latitude is available in the selection of the materials. These options are desirable but require a knowledge of mortar performance in masonry for proper selection.

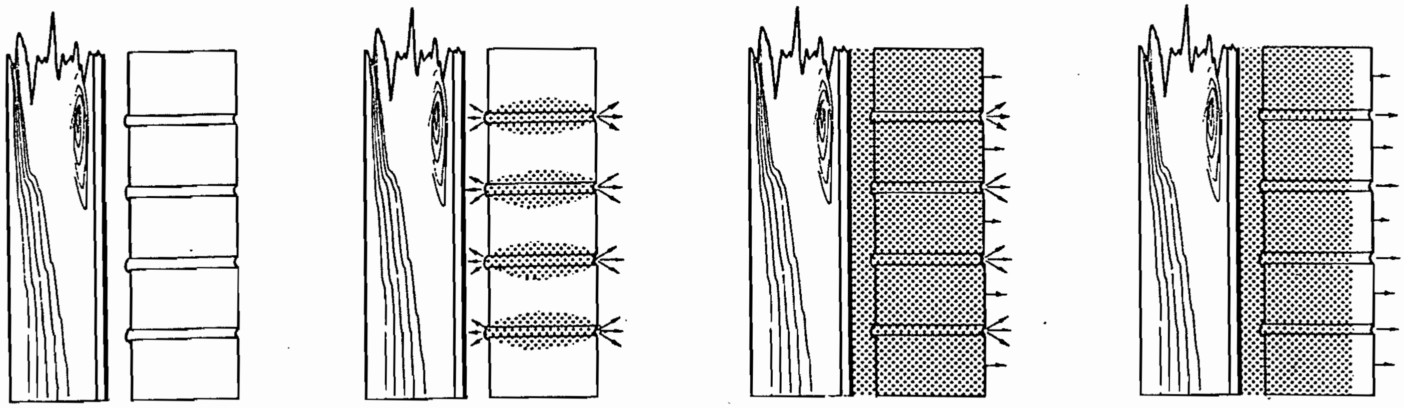
Performance of Mortar in Masonry

Regardless of the mortar mixture or masonry units selected for inclusion within the masonry, the mortar and the masonry units act together to produce the masonry. Freshly discharged from the mixer, mortar has already undergone some chemical and physical changes that will influence the load-carrying capacity of the masonry. These chemical changes commence when water first contacts the cement and ends when the mixture has insufficient water for more hydration. The plastic mixture is easily moved by trowel before it changes to a rigid mass capable of supporting loads. This transformation may be accelerated by heat or retarded by cold.

Mortar used in masonry construction exhibits different performance characteristics than laboratory-mixed and tested mortar. The main reason is that water migrates from the mortar to the masonry unit. Fig. 1 shows the various moisture conditions of masonry and the direction of moisture loss to unit and atmosphere.

When a mortar bed is placed on a masonry unit, some of the water from the mortar is rapidly removed by the masonry unit. In fact, both the absorption and migration of water are exceedingly rapid. Davison(1)** showed that the bottom half of a mortar bed on a masonry unit possessed a lower water content than the top half. The differential between top and bottom water content was related to unit suction rate (initial rate of absorption), time of exposure of mortar on unit, and masonry mortar composition.

**Superscript numbers in parentheses designate references at the end of this bulletin.



(A) Brick veneer.

(B) Moisture migrates to unit and evaporates to collar joint and atmosphere.

(C) Moisture becomes balanced inside wall and evaporation continues.

(D) Continued evaporation establishes moisture gradient.

Fig. 1. Moisture conditions of masonry.

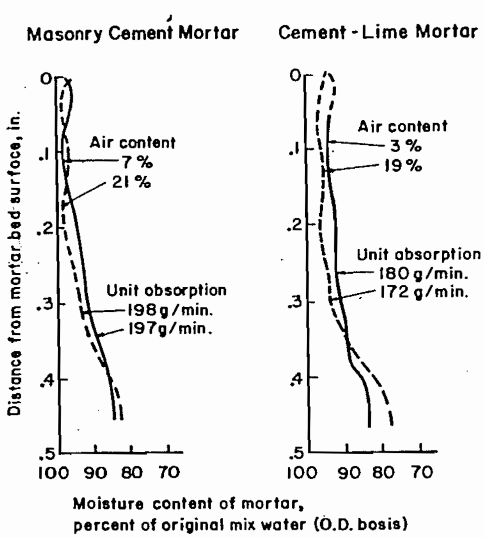


Fig. 2. Moisture gradient in mortar bed after 1 to 2 minutes contact with unit.

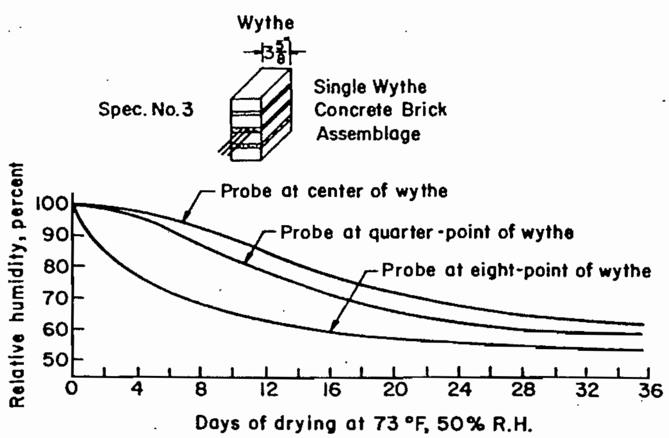


Fig. 3. Relative humidity of mortar in masonry.

Similar studies at the Portland Cement Association laboratories allowed more accurate establishment of a moisture gradient within a mortar bed. One-half-inch mortar beds on masonry units were sliced into 10 horizontal samples (each 0.05 in. thick) and oven-dried to allow calculation of mortar water content as a function of distance from the top surface of the mortar bed. As shown in Fig. 2, the data clearly established a moisture gradient; i.e., mortar at the top surface of the mortar bed remains essentially the same as mixed, whereas mortar at the bottom surface (mortar-unit interface) is appreciably reduced.

The test data in Fig. 2 also show the moisture gradient of the masonry cement and portland cement-lime mortars to be very similar and independent of air content. Approximately 20% of the total mixing water is removed from the mortar at the unit-mortar interface within 1 to 2 minutes. After the upper masonry unit is bedded, the water content of the mortar in the top portion of the bed is reduced. As the units absorb more and more water, the plastic mortar becomes a semirigid mass capable of being tooled and supporting loads.

Eventually the units and masonry mortar balance their water absorption and retention characteristics. However, the process of hydration continues to consume additional water, as does the process of evaporation. The very demanding evaporational forces continue until the relative humidity within the mortar falls below 100%, causing hydration to be slowed and eventually abated—when the humidity reaches 70% to 80%. Fig. 3 shows this relationship of relative humidity to time of exposure. Of particular interest is the relatively short period of hydration for surface mortar in comparison to the hydration period for interior mortar.

Temperature as well as humidity influence this rate of moisture loss. Under normal curing conditions and in the majority of masonry construction projects, climatic conditions are favorable for the masonry. However, dry weather increases the rate of water loss and damp weather prolongs the period of hydration. Subjecting mortar to extreme cold and damp conditions can also produce the adverse effect of reducing water loss and thus result in high-water-content mortars. These mortars are exceedingly vulnerable to early freezing with disruptive expansions. In addition, their potential for efflorescence is greatest during this period. Hot and dry climatic conditions are equally bad because these conditions promote rapid drying. Low-strength mortars with a poor bond characteristic are common under such conditions.

In portland cement-lime mortar, the lime and cement undergo carbonation after much of the initial mixing water has left the mortar. This process releases small quantities of water for further hydration or evaporation while the lime (more precisely, calcium hydroxide from the lime or cement) is converted to calcium carbonate. If water is applied to the masonry, by either sprinkling or rainfall, the cement undergoes more hydration and the calcium hydroxide goes back into solution, loses water, and is again precipitated. Reactivation of these hydration and carbonation processes becomes more difficult as both processes, singly or collectively, seal the exterior of the mortar joint.

Mortar Specifications

Existing specifications within the ASTM standards cover both mortars for unit masonry (ASTM C270-71) and mortars and grouts for reinforced masonry (ASTM C476-71). Abstracts of these specifications are shown in Tables 1, 2, and 3. Note that ASTM C270 contains both a proportion and a property specification, with no interplay between them intended or recognized. ASTM C476 contains a proportion specification and a further requirement for laboratory testing to ensure attainment of specific physical properties. All of these specifications identify mortars by type, using proportions or properties.

Prepared with an understanding of the chemical and physical properties of the various mortars and their performance in masonry, the existing specifications do help to produce mortars for quality masonry. However, one important property was omitted from the specifications and thus may be interpreted as being of lesser importance. This property, workability, is a prime consideration in producing quality mortars with various combinations of cementitious materials and sand.

TABLE 1. Mortars for Unit Masonry—ASTM C270 Proportion Specification*

Mortar type	Material proportions,** by volume			
	Portland cement†	Masonry cement††	Lime‡	Aggregate‡‡
	Portland-masonry cement mortars			
M	1	1	0	Not less than 2¼ and not more than 3 times the sum of the volumes of cement used
S	1	2	0	
N	0	1	0	
O	0	1	0	
	Portland cement-lime mortars			
M	1	0	¼	Not less than 2¼ and not more than 3 times the sum of the volumes of cement and lime used
S	1	0	¼-½	
N	1	0	½-1¼	
O	1	0	1¼-2½	
K	1	0	2½-4	

*The proportion specification governs when ASTM C270 is referred to without detailing whether the proportion or property specification shall be used. No interplay of the property and proportion specifications is recognized.

**To check proportions, water retention tests are required for laboratory-mixed mortars that contain the materials and proportions to be used in construction and have an initial flow of 100-115%. Flow after suction shall not be less than 70%. No testing of field-mixed mortars is specified.

†Portland cement or air-entraining portland cement—Types I, II, III, IA, IIA, and IIIA, conforming to ASTM C150; or portland blast-furnace slag cement—Types IS and ISA, conforming to ASTM C595.

††Masonry cements conforming to ASTM C91.

‡Quicklime conforming to ASTM C5 or hydrated lime conforming to ASTM C207.

‡‡Aggregates conforming to ASTM C144.

TABLE 2. Mortars for Unit Masonry—ASTM C270 Property Specification

Mortar type*	Cure	Properties of lab-mixed mortars**	
		Average compressive strength at 28 days, psi†	Water retention††
M	Moist-water	2,500	Flow after suction to be not less than 70%
S	Moist-water	1,800	
N	Moist	750	
O	Moist	350	
K	Air	75	

*Same specification of materials as in Table 1, with the addition of portland-pozzolan cement (Types IP and IPA) and slag cement (Types S and SA) that conform to ASTM C595. The damp, loose volume of aggregates in the mortar shall be not less than 2¼ and not more than 3½ times the total separate volumes of cementitious materials used. Mortars prepared with greater water contents will not meet the strength requirements.

**The laboratory-mixed mortars tested shall contain the materials and proportions to be used in construction. No testing of field-mixed mortars is required.

†Initial flow to be 110-115%.

††Initial flow to be 100-115%.

TABLE 3. Mortars for Reinforced Masonry—ASTM C476

Mortar type	Material proportions, by volume			
	Portland cement*	Masonry cement**	Lime†	Aggregate††
PM	1	1	0	Not more than 2¼ to 3 times the sum of the volumes of cementitious materials
PL	1	0	¼-½	

Properties of lab-mixed mortars‡	
Average compressive strength of three 2-in. cubes	Not less than 1,600 psi at 7 days‡‡ and 2,500 psi at 28 days
Water retention	Flow after suction to be not less than 70% of original flow
Air content	Not more than 18% by volume

*Portland cement or air-entraining portland cement—Types I, II, III, IA, IIA, and IIIA, conforming to ASTM C150; or portland blast-furnace slag cement—Types IS, IS(MS), ISA, and ISA(MS), conforming to ASTM C595. Air-entraining admixtures may be used that conform to ASTM C200.

**Masonry cements conforming to ASTM C91.

†Quicklime conforming to ASTM C5 or hydrated lime, Type S, conforming to ASTM C207.

††Aggregates conforming to ASTM C144.

‡Laboratory-mixed mortars shall contain the materials and proportions to be used in construction, mixed to an initial flow of 130 ±5% and in accordance with ASTM C91. No testing of field-mixed mortars is specified.

‡‡Mortars failing the 7-day strength requirement but meeting the 28-day requirement shall be accepted.

(A) Mason jar sample container. (B) Sand sample in container. (C) Mortar retarder (alcohol) in container. (D) Mortar and alcohol in container.

Fig. 4. Containers and samples required for sand, mortar, water content, and aggregate-cement field tests of mortars.

The existing specifications also fail to provide for field testing. The tests specified are limited to pre-construction laboratory evaluation of the water retention, compressive strength, or air content of small samples of laboratory-mixed mortars. Although these mortars are prepared by using the materials and proportions that will be used in construction, they definitely differ from the field-mixed mortars. Hopefully, in the future, field-mixed mortars will be field-tested, singly or in assemblages, for quality control of masonry. Such field-testing of mortars is being investigated by ASTM Subcommittee C12.2.

The subcommittee is presently concentrating on sampling and testing procedures that will allow establishment of the mix proportions and the plastic and hardened properties of mortars as prepared by the contractor. The array of mortar field tests being studied include: consistency; consistency retention using disturbed or undisturbed samples; water content; aggregate-to-cement ratio; air content; compressive strength; and splitting tensile strength. Fig. 4 shows sample containers with representative sand, a mortar retarder, and a retarded mortar sample from a construction project. Relatively simple tests of such samples will allow identification of the moisture content of the sand, the mix water content, and other mix proportions in field mortars. Collectively, the test methods provide a general indicator of mortar suitability; singly and with replications, they permit assessment of the quality control of mortars produced at the construction site.

Mortar Type Selection

The mortar type selection for a particular segment of masonry should be made by the architect-engineer team. Once the design and natural loads as well as the type of wall and masonry unit have been determined, the mortar type can be selected.

For reinforced masonry, the contract specification may simply state that the mortar shall meet the requirements of ASTM C476. This action allows the masonry contractor the option of selecting the individual mixture, PM or PL, to use. This freedom of selection of individual mixtures by the masonry contractor is recommended because the workability of mixtures and the availability of cementitious materials vary with geographical areas.

For nonreinforced masonry, mortar type is best selected by the architect-engineer team. Knowing the design criteria, the designers can select the mortar type according to the type of masonry unit desired or the allowable stresses. Such recommendations are provided in existing codes and specifications (Table 4).

Although the selection of Type M mortar for *all* masonry construction is an easy practice, it places too much emphasis on mortar strength. Mortar workability, water retention, and extensibility are sacrificed. When personal experience or performance records are not available, the author recommends the general use of ASTM C270 Type N or S mortar for nonreinforced masonry and ASTM C270 Type S or M mortar for reinforced masonry construction.

Mortar Materials Selection

To satisfy both the masonry contractor and the architect-engineer team, the mortar must possess the desirable characteristics of workability, water retention, strength (compressive and tensile bond), and durability. A mason ranks these properties as written, whereas the designers rank them in reverse order. A compromise mixture is attained when the designer selects the mortar type and the mason selects the mortar ingredients.

The person selecting the mortar and its specific ingredients should weigh the factors of mortar performance in masonry with the performance characteristics of the individual materials.

Cementitious materials. The primary role of these materials is to join the individual grains of aggregate and produce a mortar with the desired workability and strength characteristics. Mortars containing portland cement as the single cementitious material have superior rapid strength development but inferior workability and water retention, while mortars containing lime singly have superior workability and water retention but slow strength development. Combinations of portland cement and lime or masonry cements produce the proper mortar composition that gives a balance of strength, water retention, and workability for the majority of masonry construction projects.

As just indicated, portland cements contribute early-age strength to the masonry. Portland cement Types I, II, and III and masonry cements are the most commonly selected cementitious materials. Of the common portland cements, Type III possesses both chemical and physical differences that make it desirable for masonry production in cold weather. The chemical composition of this cement provides early-age strength development, and its finer grind provides more complete and more rapid hydration. Thus, Type III is desirable whenever mortars are used under adverse climatic conditions that

TABLE 4. Mortar Type Selection*

Option No. 1

Kind of masonry	Types of mortar permitted
Foundations:	
Footings	M, S
Walls of solid units	M, S, N
Walls of hollow units	M, S
Hollow walls	M, S
Masonry other than foundation masonry:	
Piers of solid masonry	M, S, N
Piers of hollow units	M, S
Walls of solid masonry	M, S, N, O
Walls of solid masonry, other than parapet walls or rubble stone walls, not less than 12 in. thick nor more than 35 ft. in height, supported laterally at intervals not exceeding 12 times the wall thickness.	M, S, N, O, K
Walls of hollow units; load-bearing or exterior, and hollow walls 12 in. or more in thickness	M, S, N
Hollow walls, less than 12 in. thick where assumed design wind pressure:	
1. exceeds 20 psf	M, S
2. does not exceed 20 psf	M, S, N
Glass block masonry	M, S, N, O
Linings of existing masonry, either above or below grade	M, S
Masonry other than above	M, S, N

Option No. 2

	Allowable compressive stresses on gross cross-sectional area (except as noted), psi				
Construction; grade of unit	Type M mortar	Type S mortar	Type N mortar	Type O mortar	Type K mortar
Solid masonry of brick and other solid units of clay or shale; sand-lime or concrete brick:					
8,000+ psi	400	350	300	200	100
4,500 to 8,000 psi	250	225	200	150	100
2,500 to 4,500 psi	175	160	140	110	75
1,500 to 2,500 psi	125	115	100	75	50
Grouted solid masonry of brick and other solid units of clay or shale; sand-lime or concrete brick:					
4,500+ psi	350	275	200	—	—
2,500 to 4,500 psi	275	215	155	—	—
1,500 to 2,500 psi	225	175	125	—	—
Solid masonry of solid concrete masonry units:					
Grade A	175	160	140	100	—
Grade B	125	115	100	75	—
Masonry of hollow units	85	75	70	—	—
Piers of hollow units, cellular spaces filled, as in Sec. 5.3	105	95	90	—	—
Hollow walls (cavity or masonry bonded). Solid units:					
Grade A or 2,500+ psi	140	130	110	—	—
Grade B or 1,500 to 2,500 psi	100	90	80	—	—
Hollow units	70	60	55	—	—
Stone ashlar masonry:					
Granite	800	720	640	500	—
Limestone or marble	500	450	400	325	—
Sandstone or cast stone	400	360	320	250	—
Rubble stone, coursed, rough or random	140	120	100	80	—

*Source: *American Standard Building Code Requirement for Masonry*, Misc. Pub. 211, National Bureau of Standards, U.S. Dept. of Commerce, Washington, D.C., 1954, pp. 8-9. Mortar types changed to ASTM C270 designations.

retard or stop hydration.

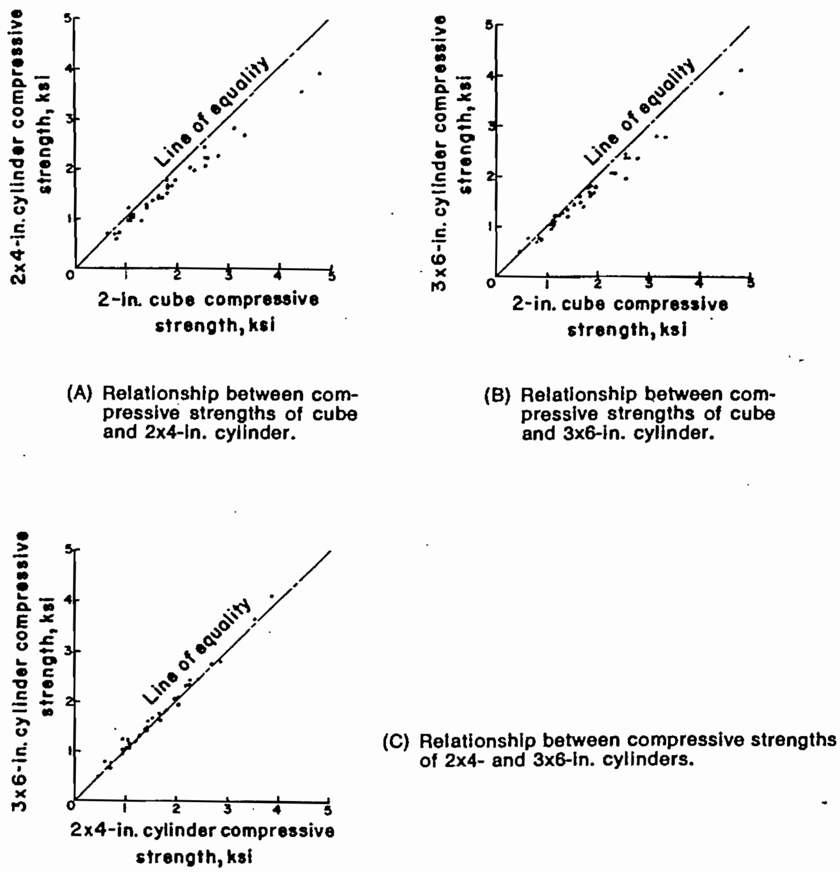
Masonry cements also contain desired chemical and physical differences. The addition of plasticizing materials during masonry cement manufacture allows control over strength characteristics while upgrading workability characteristics. Blended cements—Types IS, IS(MS), IP, and their air-entrained counterparts—are combinations of cementitious and selected supplementary materials (blended or interground) that make them quite similar to Type I and IA cements. Because they generally have a slower early-age strength gain, their use is recommended only in mortars prepared in compliance with property specifications.

Lime or quicklime in masonry mortars serves as a workability agent which, when carbonated or precipitated, becomes a cementitious material possessing low strength. Because of its extreme fineness and water-holding characteristics, lime generally complements portland cement, making the mortar more workable.

Aggregates. Aggregates are the major constituents of mortar and influence its water content as well as workability, strength development, and volume change characteristics. Sand should meet the existing specification, Aggregates for Masonry Mortars (ASTM C144), and be uniformly graded. Because a coarse, uniformly graded sand will produce the least volume change in mortar, its use is recommended over any sand with a high percentage of material in the No. 30 to 50 sieve sizes.

Admixtures. Whenever admixtures are considered for use in masonry and experience or performance records are not available, it is recommended that the admixture be laboratory-tested in the construction mortars at the temperature extremes requiring their use and then jobsite-inspected to ensure their satisfactory performance under the conditions prevailing. Materials that retard the hydration process are particularly undesirable as they reduce portland cement strength development. In addition, they generally increase the potential toward efflorescence.

Prebatched or premixed mortars. Recently wet and dry prebatched or premixed mortars have been made available to the masonry industry. The mortar supplier gives the masonry contractor two options: wet, ready mixed combinations of hydrated lime, sand, and water delivered to the construction project and then mixed with cement and additional water ready for use; and dry, packaged mortar mixtures requiring only the addition of water and mixing at the jobsite. Although economics may be a factor, both systems have merit. The mortar supplier provides quality control over a major portion of the mortar ingredients and has a higher mortar production volume than an individual masonry contractor. Therefore, the properties of particular mortars can be more frequently and economically established. With either system, since the selection of the individual ingredients is handled by the mortar supplier, mortar selection by the masonry contractor is relatively easy.



(A) Relationship between compressive strengths of cube and 2x4-in. cylinder.

(B) Relationship between compressive strengths of cube and 3x6-in. cylinder.

(C) Relationship between compressive strengths of 2x4- and 3x6-in. cylinders.

Fig. 5. Mortar strength as affected by specimen size.

Mortar Selection

Because it seems preferable to have the masonry contractor select his mortar for a particular project, the following research findings on mortar performance are given to allow him to make the proper selection.

Strength. The strength of mortar is presently the main criterion for selecting mortar type. Since compressive strength is not only relatively easy to test but also relatable to other properties, such as tensile strength and absorption, it has become the obvious acceptance-rejection criterion. Current studies, however, indicate that compressive strength is relative and greatly influenced by many factors, especially the method of test.

For instance, PCA tests of 2-in. cubes and 2x4- and 3x6-in. cylinders containing the same mortars showed that the cylinders possessed approximately 15% lower compressive strength (Fig. 5). The 2x4-in. cylinders had apparent strengths of 700 and 1,800 psi, but tests of ½- to ¾-in.-thick sections sawed from these cylinders showed strengths *in excess of 900-24,000 to 3,000-24,000 psi*, respectively (Fig. 6).

As test specimen height decreases, the strengths of all mortars become more nearly equal, especially when tested with thicknesses common for mortar joints in masonry. Laboratory test results reflect strength attainment of mortars under standard conditions; they do not reveal the strength characteristics of the mortar in masonry.

Mortar strength is further influenced by mixer type because of the effect of the mixer on mortar composition, especially its air and water content. As shown in Fig. 7, laboratory-mixed mortars containing air-entraining cementitious materials

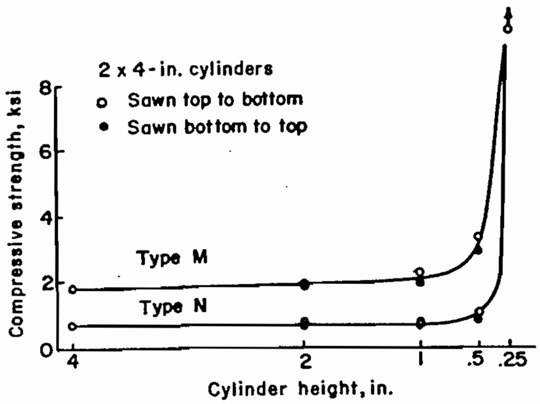


Fig. 6. Compressive strength of mortar as affected by specimen height.

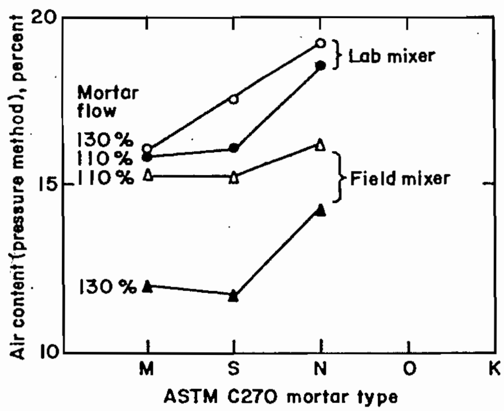


Fig. 7. Effect of mixer type on air content of portland-masonry cement mortar.

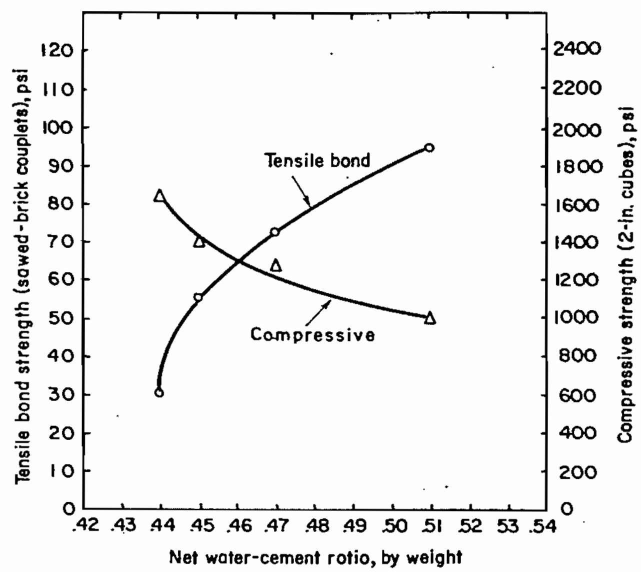


Fig. 8. Effect of water-cement ratio on the tensile bond and compressive strengths of masonry cement mortar (1:3 by volume, 7 days moist).

had higher air content than mortars mixed in a mixer similar to those used at construction sites. Arbitrarily increasing the flow of laboratory-mixed mortars from 110% to 130% caused an increase in mortar air content, but the opposite was true when the same two mortars (constant proportions but one larger in volume) were mixed in a construction-type mixer. The 28-day, cube compressive strength of these laboratory-prepared mortars decreased as their air content increased.

For the reasons given, compressive strength should not be the sole criterion for mortar selection. In fact, mortar strength should be deemphasized as allowed by ASTM C270, which states that mixing should be "with the maximum amount of water to produce a workable consistency. . . ." This inclusion recognizes the increase in tensile bond of mortars with increasing water content and constant cement content (Fig. 8). The omnipresent compromise between such desirable properties as compressive strength and tensile bond strength is apparent in Fig. 8.

Mortars mixed, cured, and tested in accordance with ASTM C270 yield compressive strengths dependent upon mix proportions, cure, individual ingredients, and conformance with testing procedures. Within a specific geographical area masonry cement mortars are more similar than they are nationwide, reflecting the emphasis being placed on those properties considered most important for that area. Considerable data are already available to compare the strengths of masonry cement mortars and their cement-lime counterparts. Specific strength data are not reported here since *compatibility* of materials and *strength attainment* of the materials are measured. However, their *performance in the masonry* is not reflected by laboratory test results.

For proper appraisal of the compressive strength of a mortar, one must know the mortar's influence on wall performance. Research[2,3] shows that brick masonry wall strength varies with mortar strength (Table 5). Extreme variation of mortar compressive strength from 75 to 2,500 psi resulted in brick masonry wall strength changes of approximately 20%. Concrete masonry wall strength is not significantly affected by masonry mortar strength.[4,5]

Water retention. This property of mortar governs the rate of water loss from the mortar to the masonry unit. In 1932 Palmer and Parsons[6] reported water loss-time relationships for many masonry units and mortar mixtures. The water retention apparatus and the present test method

TABLE 5. Relationship Between Mortar Strength and Wall Strength

Type of masonry	Compressive strength*	
	Walls	Wallettes (4x8x16 in.)
Brick masonry	Approx. 1/3 of comp. strength of the brick if cube strength is greater than 2,500 psi and Class A-inspected workmanship is involved[2]	Affected by mortar strength. Specimens of Type M mortar were 6% higher than Type S; with assemblages contained, Type N and O mortars were 29% and 47% lower, respectively, than Type S[3]**
	Approx. 1/3 to 1/2 of brick strength when brick strength is in 2,500-4,500 psi range[2]	
	Approx. equal to cube root of mortar strength, all other factors being equal[2]	
Concrete masonry	Mortar strength of little significance[4]	Mortar strength has very little effect on the axial load strength[5]

*See designated references at end of this report.

**The flexural strength was also affected by mortar strength. Type M mortar caused a 10% higher strength than Type S mortar. Types N and O caused 23% and 32% lower strengths, respectively, than Type S.[3]

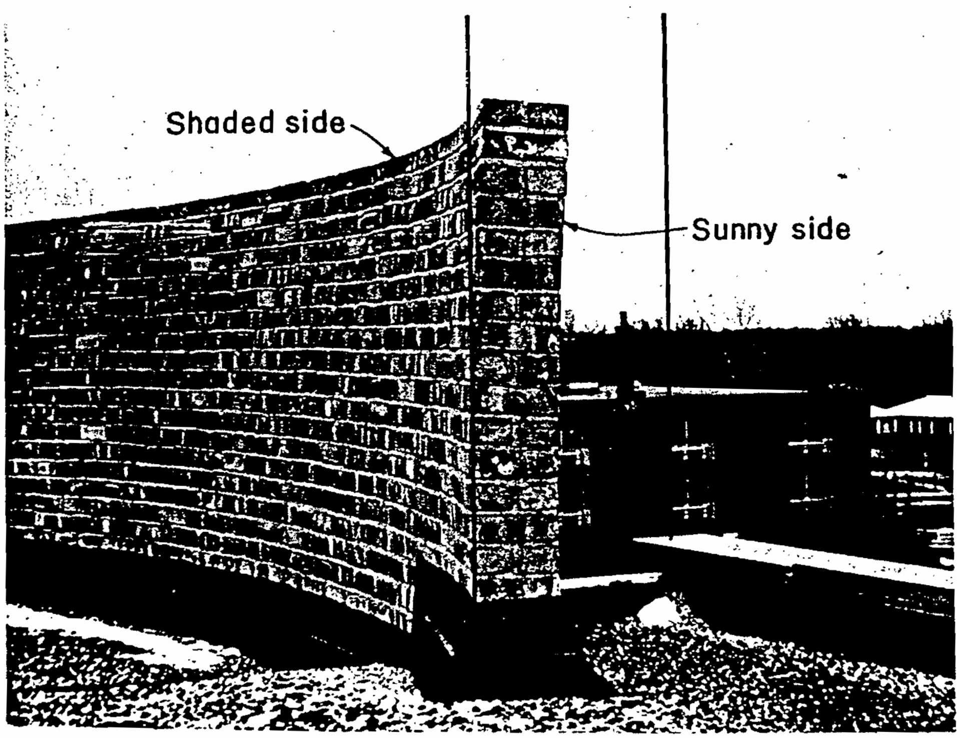


Fig. 9. Freeze-thaw damaged masonry.

that evolved from this research are considered satisfactory for product specification testing.

Studies regarding moisture migration from the mortar to the masonry unit (previously described under "Performance of Mortar in Masonry") show that water retention values must be tempered with judgment. In laboratory tests (Fig. 2), increasing the air content of mortars caused no significant change in the moisture gradient within the mortar subjected to the absorption of a masonry unit.

Durability. This is an important property reflecting the mortar's longevity. Although corrosion by aggressive environments and unsound materials may contribute to the deterioration of mortar joints, the major destruction is caused by water entering the masonry and freezing. Laboratory tests of mortar and masonry assemblages show that air-entrained mortars possess superior freeze-thaw resistance to their low-air-content counterparts. In actual structures, masonry is durable *unless* water enters the masonry through leaky downspouts, flashings, etc.

Part of this performance must be attributed to the vertical position of masonry. In addition, the building use governs the moisture content of the walls, and masonry structures are generally internally heated. Consequently, masonry walls are dry; i.e., their moisture content is below the saturation level necessary for disruptive expansion upon freezing. However, freeze-thaw damaged masonry is possible, as shown in Fig. 9.

The curvilinear masonry parapet in Fig. 9 tilts toward the sunny side. Moisture condensed and collected on the shady side; upon freezing, the ice expanded, causing the wall to tilt. Air-entrained mortars with the proper cement content are considered good insurance against such damage.

Recommendations

The following recommendations are based on present knowledge of the performance of mortar in masonry:

1. Mortars for unit masonry should comply with ASTM C270 and be selected on the basis of merit after the design criteria, including masonry structure and unit, have been determined. The mortar type should provide the desired physical properties based on existing codes, previous experiences, and test data. The mortar mixture must produce the desired physical properties in both the plastic and hardened state.

2. Mortars for reinforced masonry should comply with ASTM C476 or existing codes, and the individual mortar mixture should be based on selection or acceptance by the masonry contractor.
3. Although not presently covered in national standards, field tests of mortar should establish control of the mix proportions at the construction site. Such field tests are preferable to tests of the individual physical properties using hardened mortar specimens.

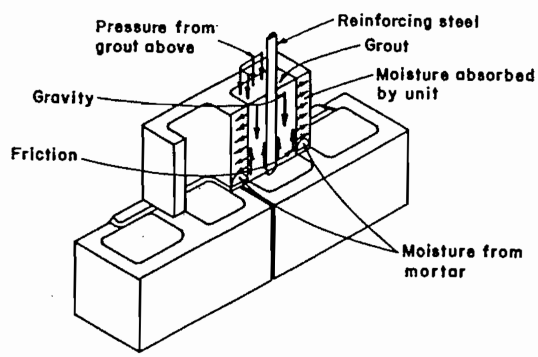


Fig. 10. Factors influencing grout performance.

GROUTS

The role of the grout in masonry construction is to join the individual masonry units with the reinforcing steel within the wall. In balancing the high tensile strength of steel with the compressive strength of the masonry unit, the grout improves the resistance of the masonry structure to loads, either directly or by transfer of stresses.

To accomplish its objective, the grout must possess fluidity; i.e., it must flow into surface irregularities within the core or structure openings and embed the reinforcing steel. After contact, the grout should lose its plasticity and fluidity rapidly and bond well with brick, concrete masonry, and steel. Grouts having high slump and equally high cement content are generally selected for inclusion in reinforced masonry.

Performance of Grout in Masonry

Since grout is a cementitious material with composition similar to masonry mortars but with a different role, it performs similarly and yet differently than mortar. The forces acting on the grout within the masonry and the exposure influences are depicted in Fig. 10.

When grouting begins, the fluid grout enters the core, cavity, or collar joint and immediately fills the volume available. The concrete, mortar, and cement paste flow to fill all cavities and surface voids and embed the reinforcing steel. If nonabsorptive units are used in the masonry, the grout undergoes settlement; i.e., the cement and aggregate settle and the mix water rises. When absorptive units are used, the grout is subjected to absorptive forces. These forces cause the grout to lose water to the masonry unit and stiffen, particularly around the perimeter of the grout space.

The rate of water loss naturally depends on the absorption characteristics, i.e., the initial rate of absorption and the absorption capacity of the masonry unit. While the unit continues to absorb water, the grout undergoes an appreciable and rapid loss of volume. Stiffening due to moisture loss then reduces grout mobility and settlement is lessened. Settlement continues until sufficient water has been removed to prevent this phenomenon.

After placement, grout vibration and revibration are recommended to obtain a denser grout. The voids, faults, and tears developed during grout subsidence are removed with these consolidation efforts.

During the entire period of grout mixing, pumping, placing, settling, and water loss, the cement in the grout undergoes hydration. The hydration process continues until the relative humidity of the grout falls below 80% approximately. Although the time when hydration ceases has not been established, the hydration period is presumably adequate to moist-cure the grout. The time is dependent on the masonry unit, grout, and ambient condition.

In addition to accomplishing its primary mission of joining the masonry unit and steel, the grout contributes to the further curing and strength development of the masonry mortar. Grout water migrates to the masonry unit and mortar, and is readily seen as wet areas within a partially grouted wall. With the passage of time, the masonry loses the water either to the atmosphere or to the hydration process.

Existing Grout Specifications

Existing specifications within the ASTM standards cover both fine and coarse grouts for reinforced masonry (ASTM C476-71). Extracts of the grout portion of ASTM C476 are shown in Table 6. Note that this standard controls grout mixtures by material proportions.

Both fine and coarse grouts are specified to include, by volume, 0 to 1/10 part of Type S hydrated lime with 1 part of portland cement or portland blast-furnace slag cement. The aggregate content of the fine grout is limited to 2¼ to 3 parts of sand conforming to ASTM C404 for each part of cementitious material. The coarse grout specification allows addition of 1 to 2 parts of coarse aggregate, as defined in ASTM C404, for each part of cementitious material.

Recognizing the need of a cementitious material for developing bond of masonry unit to steel, these specifications essentially support the construction practice of using a high-cement-content mortar or concrete mixtures with high fluidity. Although fluidity is not a specification inclusion, the importance of this characteristic must be emphasized.

It is interesting to compare the ASTM specifications with local building codes and grout mixtures reportedly used during construction. The 1967 Uniform Building Code Standards[7] states that grout "shall consist of Type M or S mortar into which sufficient additional water has been incorporated to cause the mixture to flow readily," whereas the 1970 Uniform Building Code[8] parallels the requirements of ASTM C476.

The 1961 progress report of the ASCE Task Committee on Reinforced Masonry Design and Practice[9] essentially parallels ASTM C476. It further provides that the coarse grout of C476 should be used in grout spaces in solid unit masonry 2 in. or more in minimum horizontal dimension, and in grout spaces in hollow unit masonry 4 in. or more in horizontal dimension. This report also states, "Grout should test 2000 lb. per square inch in compression at 28 days of age, as determined by the field test."

The NBS *Building Code Requirements for Reinforced Masonry*[10] specifies grout as Types MG and PG, as follows:

MG grout shall be composed of 1 part portland cement, not more than ¼ part hydrated lime or lime putty and fine aggregate consisting of 2¼ to 3 times the sum of the separate volumes of the cement and the lime used. [ASTM C476 fine grout.]

PG grout shall be composed of 1 part portland cement, not more than ¼ part hydrated lime or lime putty and 2 to 3 parts fine aggregate and 1 to 2 parts coarse aggregate. In no case shall the sum of the volumes of fine and coarse aggregate exceed 4 times the sum of the separate volumes of the cement and lime used.

A review of the available literature indicates that the existing specifications essentially parallel practice or vice versa. Some specifying agencies are more restrictive and stipulate the use of ⅜-in. gravel when the minimum horizontal space is greater than 4 in., and pea gravel when the minimum horizontal space is 2½ to 4 in. Others state that the grout should possess compressive strength in excess of 2,000 psi. The cement content of grout used was reported to range from 6.3 to 8.0 bags of portland cement per cubic yard of grout. Lime additions to grout were not reported, but one report describes the successful use of a grouting admixture.(11)

Grout Selection

The selection of a particular grout should be made on the basis of cement content of grout and the minimum horizontal dimension of the space to be grouted.

For the smallest cavities, which should not be less than 2x3 in., only fine grout should be used. When the minimum horizontal dimension is 4 in. or greater, coarse grout containing pea gravel should be used. Coarse grout may also be used for reinforced two-wythe masonry walls if the clear space is at least 2 in. As the clear space dimension increases above 6 in., the size of coarse aggregate may be increased but a high-slump conventional concrete might prove more economical and desirable than the grout mixture.

Grout Materials Selection

All of the grout materials permitted by ASTM C476 appear satisfactory, except perhaps the lime additions and air-entraining admixtures that are already essentially omitted in actual practice. Present-day machinery for grout placement and the option of using ready mixed concrete undoubtedly cause the omission of lime. The reported lowering of the bond between grout and steel associated with increased air content is probably the reason for the omission or little use of air-entraining cements or admixtures.*

In theory the lime additions would alter the fluidity, water-holding, and settling characteristics of the grout. Air-entraining admixtures would perform the same functions. Both would require one additional material to be included in the grout mixture unless air-entrained cementitious materials or masonry cement are involved.

Material selection, at present, is based on existing specifications and the performance of the grouts as established by field tests. The grout mixture can be and generally is set by laboratory tests of grout ingredients and compliance with the property limits specified. This testing has progressed from the earlier practice of coring of walls to the fabrication of grout prisms. Field tests to establish quality control of the mixtures as used at the jobsite are somewhat localized but appear to have merit.

TABLE 6. ASTM C476 Grout Specifications*

	Material proportions, by volume			
			Aggregate††	
Grout type	Portland cement**	Lime†	Fine	Coarse
Fine	1	0-1/10	2¼ to 3 times the sum of the volumes of cementitious materials	—
Coarse	1	0-1/10	2¼ to 3 times the sum of the volumes of cementitious materials	1 to 2 times the sum of the volumes of cementitious materials

*No laboratory or field testing is specified.

**Portland cement or air-entraining portland cement—Types I, II, III, IA, IIA, and IIIA, conforming to ASTM C150; or portland blast-furnace slag cement—Types IS, IS(MS), ISA, and ISA(MS), conforming to ASTM C595. An air-entraining admixture that conforms to ASTM C260 may be used.

†Quicklime conforming to ASTM C5 or hydrated lime, Type S, conforming to ASTM C207.

††Damp, loose aggregates conforming to ASTM C404.

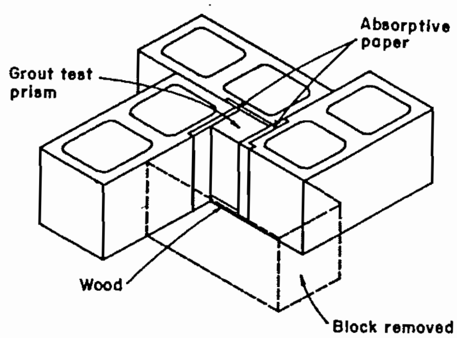


Fig. 11. Grout test prism (four 8x8x16-in. blocks required).

Methods for field-testing grouts involve grout prisms and grouted masonry assemblages. Tests of grout prisms, cast as depicted in Fig. 11, subject the grout to essentially the same conditions it is subjected to in a masonry structure and thus appear to have merit, especially when the prisms are stored at the construction site. The test results probably reflect a median compressive strength for high-lift grouts and approximately the same compressive strength for low-lift grouts.

Cold Weather Considerations

Grouts placed during cold weather are particularly vulnerable to freezing during the early period after grouting, although the wind effects normally associated with early freezing are negligible for them, as internal components of the masonry. Their high water contents, however, require protection during the early hours or days

*See Ref. 2, page 59.

after use. Grout placed during cold weather should be adequately heated or the masonry structure should be protected from freezing while the water content of the grout is sufficiently high to cause expansion upon freezing.

In practice the period for grout heating or masonry protection is difficult or impossible to establish. Probe thermometers may be embedded into the grout space to reflect temperature, but some method of measuring the moisture content of grout is needed. Testing a grout cylinder attaining 500-psi compressive strength might be considered as an alternate method, provided that the specimen is representative of the grout in the masonry structure.

Recommendations

Grout for reinforced masonry should be proportioned in accordance with existing specifications or local codes. In addition, they should be laboratory-tested to ensure conformance with the property limits specified. Field tests of grout prisms or masonry assemblages should be used to establish the quality control and environmental influences on the grout; i.e., these test results should be analyzed with consideration of the grouting operation, exposure, and ambient conditions.

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KEYWORDS: admixtures, aggregates, air entrainment, bonding, cements, compressive strength, durability, field tests, grout, masonry, moisture content, mortar (materials), relative humidity, specification.

ABSTRACT: Reviews and correlates mortar and grout specifications with the construction and performance requirements of masonry. Explains the roles of mortar and grout in terms of the development of plastic and hardened properties, commencing with materials selection. Some nonspecified physical properties are shown to be of equal or greater significance to masonry performance than those currently specified. Field testing and all-weather considerations are discussed.

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