1. ABSTRACT

Repair and strengthening of existing masonry buildings by injection grouting is a viable means to provide functional, durable, and safe structures without physically altering external aesthetics. An experimental and analytical program investigating the effect of grout injection on the structural behavior of old, unreinforced masonry is currently underway. Several different formulations of cementitious grouts were found to be useful for injection of old masonry. These grouts are used for injection into cracks in damaged masonry to restore structural capacity and can also be used to fill existing voids to strengthen deficient masonry. A procedure for injection of grouting of masonry is described, including specific descriptions of wall preparation, injection port location, grout mixing, and the injection process. A case study showing the effect of injection grouting on the compressive behavior of a masonry pier is included.

2. INTRODUCTION

Existing masonry buildings often contain voids, cracks and weaknesses which can affect the structural capacity and safety of the building. Injection of grout into cracks may be used as a form of repair following a damaging event to restore the masonry to its original structural condition. The technique can also be used to strengthen multi-wythe brick or stone masonry by injecting grout into voids in the collar joint, enhancing composite action between adjacent wythes.

Grout injection into cracks and voids in masonry is a common repair technique, but

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there is little available information regarding the effect of this treatment on masonry structural behavior. An experimental program is currently underway to evaluate grouting procedures, the suitability of different types of cementitious grouts for injection, and the effect of grout injection on structural behavior. The 3-year program is a collaborative effort between the authors and P.B. Shing at the University of Colorado, and L. Binda at the Politecnico di Milano, Italy. The main purpose of this project is to provide an increased understanding of fundamental behavioral mechanics of older unreinforced masonry and to provide quantitative data on the effect of grouting on the strength and stiffness of old masonry. This particular paper reports on the development of grouting procedures and specific mix formulations for different types of masonry repair.

3. BACKGROUND

Many different schemes have been used for repairing or strengthening existing masonry buildings. Reinforced shotcrete or ferrocement overlays are useful for strengthening or consolidation purposes but by nature this treatment covers the masonry exterior, concealing the historical appearance of the structure. Certain situations may warrant more expensive treatments such as placement of steel reinforcement grouted into cores drilled in the plane of the wall. This technique is useful for some cases but tends to create zones with widely varying stiffness and strength properties. Cementitious grouts can have properties similar to masonry and, when injected into cracks and voids, provides a simple means for restoring or improving structural integrity without altering significantly the homogeneity of the base material.

A grouting procedure developed specifically for use during seismic retrofit procedures is being used in Southern California [1]. Cementitious-based grout is injected into larger cracks and empty collar joints in multi-wythe masonry to increase composite behavior and strengthen the wall against seismic excitations. The method has been approved for use by the City of Los Angeles [2] and provides the basis for some of the procedures described below. The grout formulation specified in Los Angeles procedure works well for filling larger cracks and voids but is too coarse for penetration into fine cracks.

It is possible to fill narrow cracks provided a suitable grout is formulated. Miltiadou [3] developed several mixtures for injection of very fine cracks in masonry. This research also showed the importance of using high-energy mixers when incorporating micro-fine materials into the grout mix. Binda studied the use of injection grouting on structural behavior and durability of masonry [4]. Her initial work used an epoxy resin grout but this material was abandoned for cementitious-based grouts based on structural and environmental concerns. Tomasevic has studied the structural behavior of both stone and brick masonry walls injected with cementitious grouts. The effects of grouting were evaluated by tests on full-size wall specimens for both in-plane and out-of-plane loadings [5].

4. GROUT FORMULATIONS

The first phase of the experimental program utilized a series of standardized tests to determine the suitability of various grout formulations for injection into small cracks.
and voids which may be present in masonry [6]. Thirty-four trial grout mixes were evaluated to determine the relative fluidity, injectability, bond strength, and stability of the mixtures. The formulations described in Table 1 below were chosen as providing the optimum combination of these parameters. It was found that by carefully designing a grout mix injection of cracks from 0.08 mm thickness to voids of 12 mm and larger is possible. These grout formulations possess properties similar to the masonry being repaired, and would be economical for widespread use as a masonry repair material. Note that all mixes utilize a superplasticizer and have high water/cement ratios to provide grout which flows well into small voids and cracks.

Grouts for masonry injection can be separated into two categories: those for injection into fine cracks and those for filling of larger cracks and voids. Grout Mixes I and II are used for injection of fine cracks; spaces as small as 0.08 mm were penetrated by these mixtures. Both mixes use a Type III Portland cement (ASTM C 150), which has an average particle size somewhat smaller than more common Type I cements. Mix I produces a grout with good bond strength and is useful for most general-purpose applications. An expansive admixture manufactured by the Sika Corporation (Grout Aid) was used in this mix to offset some of the volume reduction due to water loss during the initial set period.

Table 1. Grout Formulations.

| Mix No. | Cement Type | w/c ratio | Solids (% by weight) | Admixtures
|--------|-------------|-----------|----------------------|-------------
|        |             |           | Cement | Lime | Fly Ash | Micro Silica | Sand | SP | Grout Aid |
| I      | III         | 0.75      | 100    |       |         |             |       | 2.0 | 1.0       |
| II     | III         | 1.20      | 90     |       |         |             | 10    | 2.0 |           |
| III    | I           | 1.00      | 32.1   | 4.8   | 7.9     |             | 55.2  | 2.0 |           |

1 ASTM C 150 Portland cement
2 Ratio of weight of water to weight of cement
3 Percent by weight of cement
4 SP = Superplasticizer (modified napthalene sulphonate formaldehyde base)

Grout Mix II is very fluid and penetrates well into even the finest of openings. Addition of microsilica results in a strong, dense grout with excellent bond capacity to the masonry. The microsilica has the added benefit of being slightly water retentive, reducing the tendency of the grout to stiffen prematurely while flowing through narrow openings.

Aggregate in the form of a fine silica sand was used in Mix III, developed for injection of voids and cavities larger than about 5 mm. The addition of sand reduced grout shrinkage and resulted in a more economical mix, but limited the size of injectable cracks. A more economical Type I cement (ASTM C 150) is the main binder; fly ash (ASTM C 618 Class F) and lime (ASTM C 207 Type S) also have cementitious properties but were added mainly to act as stabilizing agents for keeping the sand in suspension. Cracks as small as 3 mm were found to be filled with this mixture and cracks larger than about 5 mm were filled with regularity. Particle size distribution of the silica sand used is shown in Figure 1.
5. EQUIPMENT

Grout mixing is a critical step in the preparation process. Adequate mixing procedures and high-shear mixing equipment are necessary to break up agglomerations of cement, fly ash, and microsilica particles. Proper mixing will result in a grout with superior injectability properties. In this study, grout was mixed using a high-shear drill-mounted mixer operating at 1500 to 3500 rpm. The highest speed possible should be used to break the mix components into individual particles.

A pressure-pot is used for injecting small grout volumes into finer cracks. The pot should have a regulator and pressure gage to verify and maintain proper injection pressure. Use a piston-type pump with integral mixer for injecting grouts with aggregate or when large volume takes are expected. The injection hose should terminate in a wand with appropriate fittings for attachment to injection ports or should have an expandable packer or rubber tip for sealing in injection holes.

The use of a hollow-core drill bit with vacuum chuck (see Figure 2) is recommended for drilling injection holes. Normal rotary bits have the tendency to force dust and drill...
cuttings into the crack being drilled thus sealing the crack from grout penetration. This apparatus allows residue to be removed during drilling with the aid of an attached vacuum, resulting in very clean injection port holes and leaving cracks wide open for further injection. Percussion hammer-drills can damage masonry and should not be used for drilling holes into sensitive or historic masonry.

6. INJECTION GROUTING PROCEDURES

A standard program for specimen preparation, grout mixing, and specimen injection has been developed and used throughout this project to provide a consistent base for evaluation of grout mixtures. These steps are outlined below and should provide a good basis for injection repair of large scale specimens, however, it must be stressed that it will be necessary to adapt these procedures to varying situations. Guidelines summarized below are based in part upon recommendations provided by the City of Los Angeles [2].

6.1 Initial Survey and Repair. Before proceeding with any repair or retrofit program, conduct a thorough assessment of material condition throughout the area to be repaired. This survey will not only identify potential areas for treatment, but will also serve as a basis for post-repair quality verification. The initial survey would include mapping the extent and size of any visible cracks, mortar joint delaminations, or other damage. Units which exhibit extensive cracking, spalling, or crushing should be replaced. Mortar joints must be tight and capable of resisting injection pressure and, if necessary, deficient mortar should be raked and the joint repointed. Use units and mortar having a composition and strength similar to existing materials for repairing damaged areas.

6.2. Nondestructive Evaluation. Nondestructive testing should be a part of all repair programs, and can be used to identify subsurface cracks and voids before repair, as a means of verifying grout penetration during injection, and as quality control technique following repair. Methods which use stress wave transmissions (such as ultrasonic pulse velocity, mechanical pulse transmissions, and pulse-echo techniques) have proven to be quite useful for location and characterization of sub-surface cracks and voids [7]. Pre-repair mapping of direct (through-wall) pulse velocity can provide an indication of subsurface voids and flaws and can provide some guidance when determining areas for injection.

6.3. Crack Injection Ports. Injection of cracks will require placement of either surface-mounted or drilled injection ports approximately 70 to 300 mm on center. The spacing and placement of ports is dependent upon both the width and roughness of the crack. Typical placement of drilled and surface ports are shown in Figure 3.

Use drilled ports about 70 mm on center for cracks less than 1 mm wide. Injection holes should be 6 to 12 mm diameter and are best placed in a mortar joint, where the crack intercepts a head joint or bed joint. Drill only about 50 mm deep into these cracks without intercepting the collar joint. Ports are placed within the drilled holes as near to the surface as possible to aid in removal following grouting. Silicone sealant may be used to seal around the port or, alternatively, the material used to seal surface-breaking cracks can be used to also seal around the port.
Figure 3. Placement of collar joint injection holes, drilled ports for injection of narrow cracks, and surface ports for injection of wide cracks.

Surface-mounted ports are easier to install, result in less disfiguration to the masonry, and can be easily removed. Surface-mounted ports placed up to 300 mm on center may be used for cracks which are wider than 1 mm. Surface ports are placed over the crack, on a masonry unit where possible (Figure 3). These ports are tacked in place using hot-melt glue, and later covered completely with epoxy during the crack sealing process.

6.4. Collar Joint Injection Holes. Holes for injection of collar joints should be at least 3/8” in diameter for adequate grout flow. These injection holes are best located at mid-height of a head joint, where there is the least likelihood for mortar fins or bridging blocking the collar joint. Collar joint injection ports are inserted into the drilled hole, and sealed with silicone or epoxy. If the injection wand is self-sealing (terminating in a packer or rubber tip) a plastic port is not necessary. Spacing of collar joint injection ports is dependent upon inner quality of the masonry: grout flowing well through a wide, clear joint will require fewer injection holes than narrow, obstructed joints. The optimal spacing of injection holes can only be determined by experience or trial injections on small wall sections. An initial spacing of 400 mm horizontally and 150 to 300 mm vertically is recommended. The location of injection ports along adjacent vertical lines should be staggered such that ports are located in each course (Figure 3). In cases of multi-wythe walls with multiple collar joints, injection holes should be drilled into each collar joint, from either one or both sides of the wall.

6.5. Crack Sealing. All surface-breaking cracks and mortar joint delaminations must be sealed prior to injection to prevent grout leakage at the surface. Any suitable sealant material may be used, but it is important that the material be relatively rapid setting and must be capable of resisting injection pressure. For historic applications the seal-
ant material must be removed completely following injection such that the surface appearance is not altered. Take care during application to prevent these sealants from penetrating deep into the cracks.

A number of different crack sealants were evaluated during this program, including silicone sealants, butyl-rubber caulk, a flexible latex surface treatment, vinyl spackle paste, and polyester resin epoxy. The vinyl spackle has the distinct advantage of being relatively easy to remove with water and a stiff brush, however, being somewhat water soluble, occasional leakage occurred during injection. Polyester resin proved exceptional at sealing cracks, has a rapid hardening time, and is easily applied with a small spatula.

6.6. Cleaning and Saturation. When the surface sealant has had sufficient time to cure, the wall is flushed with water to remove as much dust and debris as possible, and also to saturate the masonry. Regulate city water pressure to about 0.1 MPa and begin flushing at the topmost port, continuing downwards to clear any internal debris out open ports below. Flush the wall until water flows clear from lower ports. This step saturates the masonry and helps to alleviate the problem of grout stiffening quickly due to moisture loss following injection. The masonry should be in a saturated surface-dry condition at the time of injection and it is usually best to flush debris from the wall 24 hours prior to injection. Lightly flush again to saturate the repair area about 30 minutes prior to grout injection. At this time the wall surface should also be sprayed with water to prevent grout spills from being absorbed into the surface.

6.7. Grout Mixing and Control Tests. An initial mixing time of 3 minutes was found to be sufficient using the apparatus described above. Remix periodically at approximately 5 minute intervals to keep all mix particles in suspension. Quality control or material characterization tests are conducted immediately following mixing. Viscosity measured using the Marsh Funnel viscometer (American Petroleum Institute Recommended Practice 13 (b)) provides a good indication of injectability and is suitable for use with very fluid grouts. A simple flow test described in Los Angeles RGA 91-1 [2] is used for grouts with sand aggregate. In this test a 50 mm diameter x 100 mm cylinder is filled with grout and poured onto an impervious surface from a height of 300 mm. The diameter of the resultant grout puddle provides an indication of grout fluidity. Small samples for compression or tensile splitting tests may also be useful for characterization or quality control tests however if cast in nonabsorbent molds will not reflect in-place properties of the grout.

6.8. Grout Injection. A low injection pressure of 0.05 to 0.10 MPa is used for injection of cementitious grouts. Injection utilizing high pressures tends to trap pockets of air within the grout and can cause rapid separation or filtering of solids as the mixture enters a crack, whereas low pressures allow the grout to seep slowly into available openings. Injection pressures should also be kept as low as possible to avoid causing additional damage from pressure build-up during injection.

Injection of collar joints begins at the lower-most injection hole, using a low shrink grout mixture such as Mix III described above. Holes located above the injection point are plugged with a wooden dowel when grout flows from them and injection continues until refusal, applying pressure for an additional 30 to 60 seconds after refusal to further consolidate the grout. Each hole is capped following injection, with the process

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repeated at each collar joint hole, continuing in an upward direction until all collar joint ports have been either pressurized or have had grout flow from them. A maximum lift height of 0.5 to 1 m is advisable to avoid build-up of excessive hydrostatic stresses.

When all large voids have been filled, a second grout mix such as Mix I or II is prepared for filling of fine cracks. Crack injection proceeds in a similar manner, from the bottom-most port to the top port, until cracks are filled completely. If the holes are spaced correctly, grout should flow out of the adjacent 1-2 ports before refusal. The highly absorbent nature of old masonry causes the grout to stiffen quite rapidly after pressure is removed and the entire process should proceed in continuous fashion, with no time lapses during injection of any single crack.

6.9. Surface Cleaning. Surface cleaning should be conducted during injection by flushing any spilled grout from the surface. Immediately following injection, any remaining surface stains should be removed using water and a stiff brush. In this manner the masonry surface will retain, as much as possible, its original surface appearance.

6.10. Removal of Ports and Crack Sealants. Wooden dowels used for plugging collar joint holes can be removed after about 30 minutes, but allow injected grout to cure for a minimum of 24 hours before removing plastic injection ports and surface sealants. Vinyl plaster sealants are semi-water soluble and can be removed with water and a stiff brush. Epoxy sealants are best removed by using a heat gun to soften the material to such a state that it can be scraped off easily using a putty knife.

6.11. Repair of Injection Holes. Holes left in mortar joints at injection port locations should be repaired. A stiff mortar, similar in color and composition to the original mortar, should be packed firmly into injection holes, flush with the surrounding mortar. The port hole should be flushed with water and should be wet, but not saturated, prior to mortar placement.

6.12. Post-Repair Tests. The final step is verification of the adequacy of the grout injection. Nondestructive and in situ tests should be conducted and compared to pre-repair results. Nondestructive pulse velocity testing may indicate insufficient grout penetration; in such a case, additional injection will be required. In situ tests such as flatjack or shear tests conducted at this time provide a measure of material properties in the repaired state to be used during engineering analyses.

7. EFFECT OF GROUT INJECTION ON MASONRY COMPRESSION BEHAVIOR

A series of eight masonry piers were constructed at the University of Colorado as part of a research project investigating the effect of injection grouting on masonry behavior [8]. The pier specimens were constructed using solid pressed clay units reclaimed from a circa 1915 structure. Mortar with proportions of cement lime:sand of 1:2:9 (by volume) was used to simulate old, deteriorated mortar. The test specimens were constructed with a quality reflecting construction practices typical of the early 1900's and had furrowed bed joints and partially filled head joints. The interior wythe consisted of broken, uneven units, with collar joints being predominately empty. Construction of a masonry pier is shown in Figure 4.
Each of these piers were loaded to failure in compression to determine the compressive characteristics of old unreinforced masonry. Immediately following load removal the piers were re-loaded to determine the compressive behavior in the damaged state. Piers were removed from the test apparatus, and any severely crushed units were re-
Grout was injected into the collar joint and also into cracks caused during the initial loading. Following a 28-day (minimum) curing period the piers were again loaded in compression to failure.

Shown in Figure 5 are stress-strain curves obtained for Pier 6. Cracks in this pier were injected using Grout II described above. Comparison of the behavior of the repaired pier with that of the as-built and damaged behaviors provides an indication of the effect of injection grouting as a repair technique. These results represent the typical condition, where the repair process was effective at restoring the initial stiffness of the masonry. Injection grouting also improved the compressive strength by 30 percent over that measured for the damaged pier and, even though 100 percent of the original strength was not restored, injection grouting appears to be a viable technique for restoring masonry compressive behavior. Most importantly, the behavior in the working stress range (up to about 1.5 MPa) has been recovered completely.

8. CONCLUSIONS

Injection of cement-based grout is an effective technique for repairing damage in unreinforced masonry. Different types of grouts have been developed for filling spaces ranging in size from very narrow cracks to empty joints and large voids. For most cases grout injection will not increase the masonry strength beyond that of undamaged masonry and, in fact, often will not completely restore behavior to that of the undamaged state. The technique is capable of strengthening damaged masonry and will consistently restore compressive behavior up to about 80 percent of the original masonry strength.

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10. REFERENCES


