Laboratory Design Program for Seismic Ground Response Improvement with Mass Concrete Fill

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SUMMARY:
Sensitivity analyses for a critical facility near a credible fault source suggested that the in-structure response spectra and corresponding costs for structures, systems, and components could be significantly reduced by improving the foundation subgrade materials. A plan was selected to remove the in-situ materials and replace it with a mass concrete fill (MCF). A laboratory, mix design program was performed to obtain an MCF mix that achieved the target dynamic properties and optimal workability, while minimizing heat of hydration concerns. Resonant column and compressive strength tests were performed in the laboratory on cylinders made using a range of MCF mix recipes. While traditional concrete mix designs typically do not consider dynamic properties as a design criterion, this case study illustrates that dynamic testing can and should be an integral part of mix design for seismic ground response improvement of important and critical facilities.

Keywords: shear wave velocity, shear modulus, seismic testing, mass concrete fill, free-free resonant column, compressive strength

1. INTRODUCTION

1.1. Background

The proposed critical facility is predominately below grade with maximum plan dimensions of about 310 by 350 feet (94 by 107 meters). The facility owner established the foundation bearing elevation based on various functional, operational, and security criteria. At this elevation, the foundation for the proposed facility would bear directly on a poorly-welded layer of volcanic tuff approximately 60 feet (18 meters) thick. Field seismic measurements revealed that the tuff layer has a small-strain, shear wave velocity (V_s) of about 1,050 feet per second (ft/sec) or 320 meters per second (m/sec). At the expected earthquake strain, the V_s reduces to as little as 300 to 500 ft/sec (91 to 152 m/sec). In-structure response spectra (ISRS) results developed during preliminary soil-structure interaction (SSI) analysis suggested spectral accelerations as high as 10g to 20g for various structures, systems, and components (SSC) of the facility.

A sensitivity analysis performed by others suggested that the very high ISRS spectral accelerations could be significantly reduced if the stiffness (and corresponding shear wave velocity) of the tuff bearing layer were increased. The sensitivity analysis indicated an improvement of the bearing layer to a target V_s of 4,000 ft/sec (1,219 m/sec) would approximately halve the ISRS spectral accelerations of the SSCs. The analysis indicated that further increase of the bearing layer V_s would result in only marginal improvement in the ISRS.

The facility owner commissioned a study to evaluate options for ground improvement to achieve the target V_s of 4,000 ft/sec or above for the entire 60-foot thick layer. Numerous options were evaluated, including in-situ and excavation/replacement ground improvement. Various criteria were evaluated including: improvement of V_s , volumetric consistency, quality assurance, confidence in the method, industry experience, schedule, and cost. The study recommended that the best option for this facility was complete excavation of the tuff layer and replacement with a cementitious material. After further discussions with the facility owner, mass concrete fill (MCF) was selected as the replacement material.

2. MASS CONCRETE FILL DESIGN CONSIDERATIONS

The primary objective of the laboratory program was to develop an efficient, workable MCF mix with acceptable dynamic properties. There are several other engineering concerns for the design mix, many of which cannot be met by simply adding more portland cement to achieve higher dynamic stiffnesses. Special consideration was given to the constructability of the mix relative to the schedule of the project and critical factors such as heat of hydration of a large thermal concrete block. The following subsections discuss the effort to design an MCF mix based on dynamic considerations and optimize its properties for workability and other engineering concerns.

2.1. Estimation of Dynamic Properties

As discussed in concrete design publications such as ACI 211.1-91, Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete, key design parameters such as the water-cementitious ratio (w/cm) are typically decided based on the target mix compressive strength. Since dynamic properties are not commonly used as one of the mix design objectives, it was useful in this project to first research case histories and correlations of static property-based concrete design and then translate those results into dynamic properties.

There is a storied history of MCF use in high hazard structures, notably dams. Typical engineering properties of MCF dams, including compressive strength, static modulus of elasticity or Young's modulus (E), Poisson's ratio, and density are presented in ACI 207.1R-96, Mass Concrete (Tables 3.3.2 and 3.7.1). This database includes concrete mixes constructed with large aggregate size with measured static modulus and compressive strength values for comparison. These comparisons for 28-day static E converted to shear wave velocity and a trendline are presented in Figure 2.1 as Method 1.

The static E may also be related to concrete compressive strength using industry accepted equations as described in ACI 318-02, *Building Code Requirements for Structural Concrete and Commentary.* The relationships shown in Equations 2.1 and 2.2 were developed for normal weight concrete as:

$$E = 57{,}000\sqrt{f_C^{'}} \qquad (2.1)$$

$$E = \gamma^{1.5} * 33 * \sqrt{f_C^{'}} \qquad (2.2)$$

where:
E = Static Modulus of Elasticity (lbs/in^2),
f'_c = Compressive Strength (lbs/in^2), and
γ = Unit Weight (lbs/ft^3).

The graphical representation of V_s developed from these two equations using 28-day compressive strength values of the ACI-referenced dam sites are presented in Figure 2.1 as Method 2 and Method 3, respectively. Where required, an average unit weight of 150 lbs/ft^3 (2.4 g/cm^3) and a Poisson's ratio, ν, of 0.20 was used for Methods 2 and 3.

All three methods require conversion of elastic modulus to shear modulus and then shear wave velocity. As referenced in Richart et al. (1970), shear modulus, G, is related to E and ν as shown in Equation 2.3 by:

$$G = \frac{E}{2(1+\nu)} \tag{2.3}$$

Equation 2.3 assumes that the material is a homogeneous isotropic linear elastic material. The shear wave velocity of a material, V_s , is related to G and E in Equation 2.4 from Richart et al. (1970) as:

$$V_s = \sqrt{\frac{G}{\gamma/g}} = \sqrt{\frac{E}{2(1+\nu)(\gamma/g)}} \tag{2.4}$$

Where:
γ = Unit Weight, and
g = Gravitational Acceleration.

It's important to note that E (and hence G) is based on static, high-strain tests and that some non-linearity (or modulus reduction) is anticipated for these materials. Research by Bay and Stokoe (1992) indicated a concrete static elastic modulus of about 11 percent lower than the dynamic elastic modulus. Other researchers such as Mindess and Young (1981) noted as much as 20 to 30 percent lower static E than the dynamic E. However, this larger difference could also be due to the dynamic measurements inadvertently being performed with constrained compression waves. Nonetheless, these case-history values were useful in developing a rough order of magnitude estimate of small-strain dynamic properties.

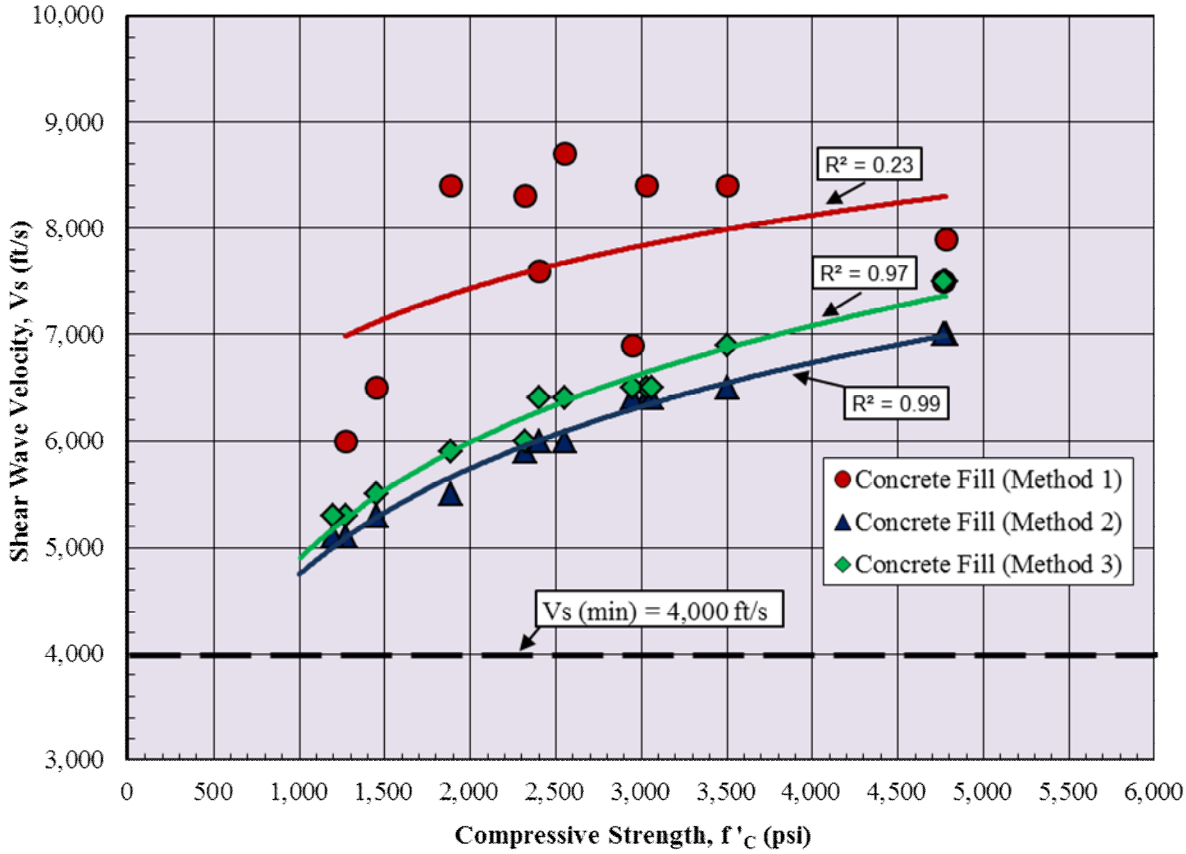

Figure 2.1 – Variation of Shear Wave Velocity with Compressive Strength for MCF

Based on the shear wave velocity results correlated in our work with engineering parameters at dam sites where MCF was used, and considering other published correlations, a target compressive strength range of 500 to 1,500 psi (3,447 to 10,342 kPA) was selected to achieve a V_s greater than 4,000 ft/s. With the understanding that significant strength gain would continue over a longer period of time (90 days or greater) due to the high percentage of fly ash, the mix recipes were designed to reach the target compressive strength at 28 days to reduce the likelihood that the cure-time of the MCF could adversely affect the construction schedule.

2.2. Mix Design

Standard industry guidelines and engineering judgment were used in developing a mix that would achieve the target shear wave velocity, compressive strength, and optimal workability. The proportion of water and admixtures, hence workability, was optimized by visually examining each mix during the small trial batches and making small recipe adjustments as needed prior to production batching. Various challenges were expected with these types of mixes including segregation, consolidation, bleed water, and lack of plastic mobility. The workability was characterized by: (a) good cohesion, with minimal segregation, (b) good consolidation, (c) good mobility during consolidation, and (d) low variability during testing.

These mix design parameters and associated values are summarized in Table 2.1. These design criteria are derived from published guidance documents, supporting calculations, and our subject matter experts. Eight mix designs were developed for batching as shown in Table 2.2.

Table 2.1 - Target Parameters for Concrete Testing

	Parameter	**Criteria**	**Commentary**
1	Target Design Compressive Strength, (f ’c)	f ‘c = 500 to 1,500 psi (3,447 to 10,342 kPA)	See Section 2.1 Discussion
2	Design Slump	1 to 3 inches (2.54 to 7.62 cm), 2-inch (5.08-cm) median value	Lower slump reduces water demand and thus the amount of cementitious material while maintaining a given water-cementitious materials ratio (w/cm), facilitating heat reduction of the mix.
3	Maximum Aggregate Size	Large as feasible, 1 to 3 inches (2.54 to 7.62 cm) selected.	Three-inch aggregate represents the upper limit of locally available commercial aggregate and is desirable to reduce the water demand due to smaller surface area that needs to be covered by the cement paste.
4	Water to Cementitious Material Ratio (w/cm)	The MCF will be located below the building and won’t be exposed. As such, there are no w/cm limits.	The w/cm ratio was chosen based on workability (a desired range of slump). The estimated target w/cm ranged from about 0.3 to 0.7 depending on the volume of cementitious material.
5	Water and Entrained Air	Mixing water based on workability, maximum aggregate size and slump range. A design entrained air content of 4.5% (range of 3% to 6%) selected.	Larger aggregate increases the potential for segregation. Using engineering judgment we limited segregation by increasing the percentage of sand, using air-entraining admixture to enhance the cohesiveness and mobility, and using water-reducing retarding admixture to enhance the consolidation of the mix.
6	Coarse and Fine Aggregate Content	ACI 211.1 (Table A5.3), ASTM C33	Coarse aggregate gradations with size ranges of No. 4 sieve to 3/4 in., ¾ in. to 1 ½ in., and 1 ½ in. to 3 in. were utilized for the design with a combined 65% of the aggregate volume. The fine aggregate consisted of washed mortar sand for 35% of the aggregate volume.
7	Type I/II Portland Cement (PC) and Class F Fly Ash (FA) Content	Cementitious Material ranged from 200 to 500 pounds per cubic yard (pcy)	Fly ash content was varied from 40% to 50% by weight of the total cementitious material to reduce heat of hydration and the potential for alkali-silica reactivity (ASR), and reach design strength within an acceptable time frame while enhancing the workability and the overall performance of the mix.

Table 2.2 – Cementitious Content of MCF Mix Designs

Mix No.	Total Cementitious Content (pcy)	Type I/II Portland Cement (pcy)	Class F Fly Ash (pcy)	Type I/II Portland Cement (%)	Class F Fly Ash (%)
1	200	120	80	60	40
2	300	180	120	60	40
3	400	240	160	60	40
4	500	300	200	60	40
5	200	100	100	50	50
6	300	150	150	50	50
7	400	200	200	50	50
8	500	250	250	50	50

2.3. Laboratory Testing

To validate our MCF mix designs and develop the required correlations, a laboratory testing program was undertaken for the eight mixes presented in Table 2.2. Six-inch (15.2-cm) diameter by 12-inch (30.5-cm) long cylinders were cast for each of the mix designs and cured in a temperature-controlled water bath. The free-free resonant column (Fr-Fr) test was used to evaluate dynamic stiffness. The Fr-Fr test is quick to perform and is non-destructive, allowing for the same cylinders to be used for all test events. Strength was measured using the concrete compression test. Since the compression test is destructive, separate cylinders were needed for each test event.

2.3.1 Resonant Column Free-Free (Fr-Fr) Testing

Laboratory resonant column tests with free-free boundary conditions (Fr-Fr tests) were performed on MCF test cylinders from each of the eight mix designs. Tests were performed on cylinder pairs from each MCF mix design at curing times of 3, 7, 28 and 90 days after the cylinders were cast. Discretionary Fr-Fr tests were also performed on cylinder pairs at a curing time of 5 days and later tests were performed for one cylinder of each mix design at about 185 days. The test measurements included shear wave velocity (V_s), unconstrained compression wave velocity (V_c), material damping ratio in shear ($D_{s\ min}$), and material damping ratio in unconstrained compression ($D_{c\ min}$). Constrained compression wave velocity (V_p) measurements were also performed with the same test set-up, but direct travel times were used instead of the resonance method.

2.3.2 Compressive Strength Testing

Compressive strength tests were performed on MCF cylinder pairs from each mix design at curing times of 3, 7, 28 and 90 days to compute average cylinder strength in accordance with ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. Tests were also performed on singular discretionary samples at 5 days and on sample pairs at about 200 and 385 days. The discretionary tests were used to better define the relationship of compression strength versus curing time and the corresponding relationship with shear wave velocity. All MCF cylinders subjected to compression testing were capped with sulfur.

3. DISCUSSION OF MCF MIX RESULTS

3.1. Consistency and Workability Relationships of MCF Mixes

Testing was performed on the freshly mixed MCF, after wet sieving over a 1.5-inch sieve. All eight mixes satisfied the fresh property testing requirements for each mix performed for the MCF mix design program. Slump values ranged from 1 inch to 2.5 inches (2.54 to 6.35 cm) and air contents ranged from 2.5 to 6 percent. The unit weight ranged from about 143 to 149 lbs/ft^3 (2.2 to 2.4 g/cm^3).

A mix is considered to be at its optimum consistency when the water content used in a given batch of concrete had been optimized to the desired slump range. Figure 3.1 illustrates the as-batched water to cementitious material ratio (w/cm) and slump versus the total cementitious materials, specifically the sum of portland cement (PC) and fly ash (FA). This chart indicates that, as the amount of total cementitious content is increased, the required slump or optimal workability may be achieved at a lower w/cm. The chart also indicates the point of optimal workability for a given total cementitious content and w/cm. This relationship is useful for refining the water demands for future mixes.

All of the mix designs were required to achieve a level of workability that would enhance the technical and constructibility performance of each MCF mix design. While a detailed discussion of mix consistency is beyond the scope of this paper, we note that only the lowest cementitious content mixes (Mix Nos. 1 and 5) did not meet the constructability criteria. These mixes had fair to poor workability and little to no cohesion which made it difficult to manage segregation. Therefore, more time and energy were required to consolidate these low-mobility mixes and their use was not recommended from a performance perspective.

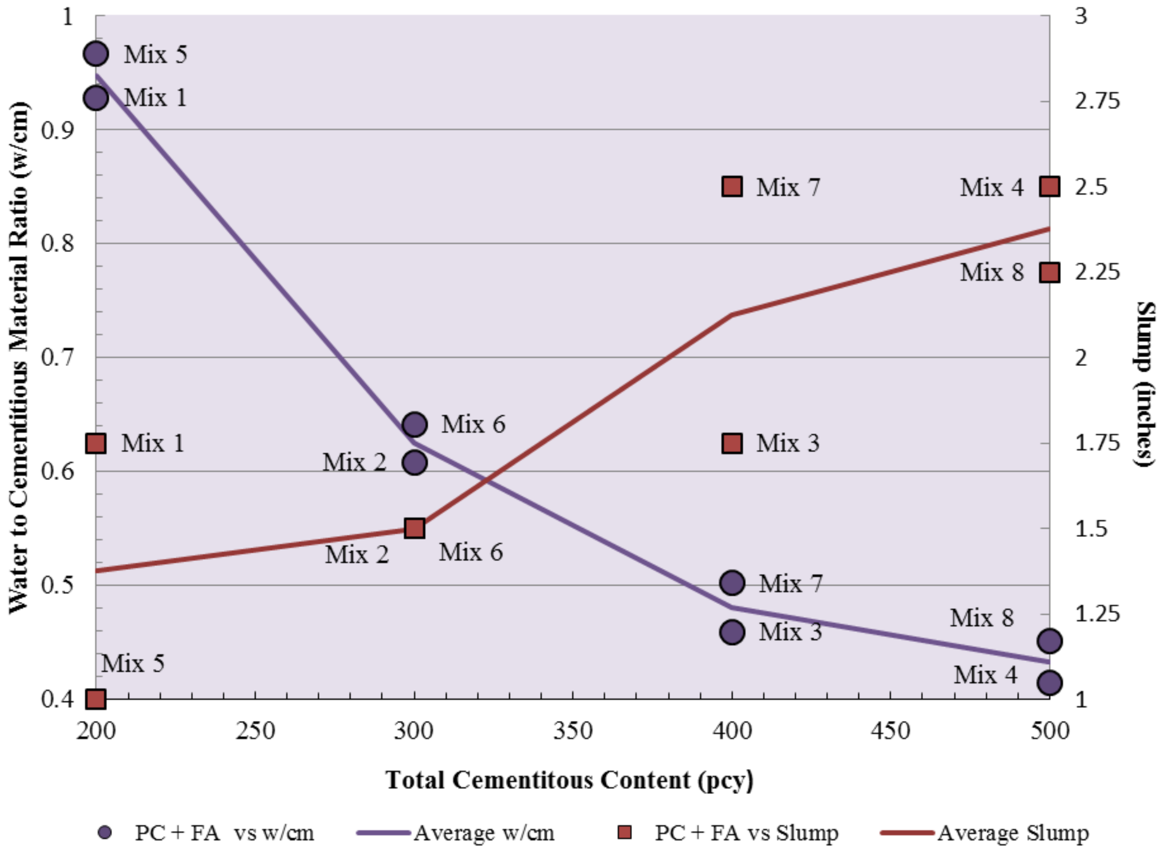

Figure 3.1 – Workability Relationships for MCF Mixes

3.2 Dynamic Test Results

The variation of shear and unconstrained wave velocity, V_s and V_c, respectively, with log curing time is shown in Figure 3.2. For clarity, only the results of Mix Nos. 5 through 8 are presented. The calculated Poisson's ratio, ν, through the relationship of V_s and V_c ranged from 0.21 to 0.27 for all eight mixes. The results of V_p, $D_{s\ min}$, and $D_{c\ min}$ are not presented because of space limitations. Due to the use of a water-reducing/retarder admixture, initial setup of the MCF was delayed until about one to two days after initial casting. Fr-Fr tests performed on curing day three indicated, however, there was a rapid increase in shear wave velocity after initial set-up. Mix Nos. 1 through 8 all met the specified target shear wave velocity value of 4,000 ft/s (1,219 m/sec) at the three-day curing age.

After about the five-day curing time, all MCF mixes appeared to have a linear increase in shear wave velocity with logarithmic time. The data trend through 185 days indicates a continuing pozzolanic contribution from the high percentage of fly ash. As anticipated, V_s is also proportional to the cementitious content of the MCF mixes. Mix No. 4 exhibited the highest average shear wave velocity of approximately 8,200 ft/s (2,499 m/sec) at 28-days curing time. Mix No. 5 resulted in the lowest average shear wave velocity of approximately 6,300 ft/sec (1,920 m/sec) at 28-days curing time.

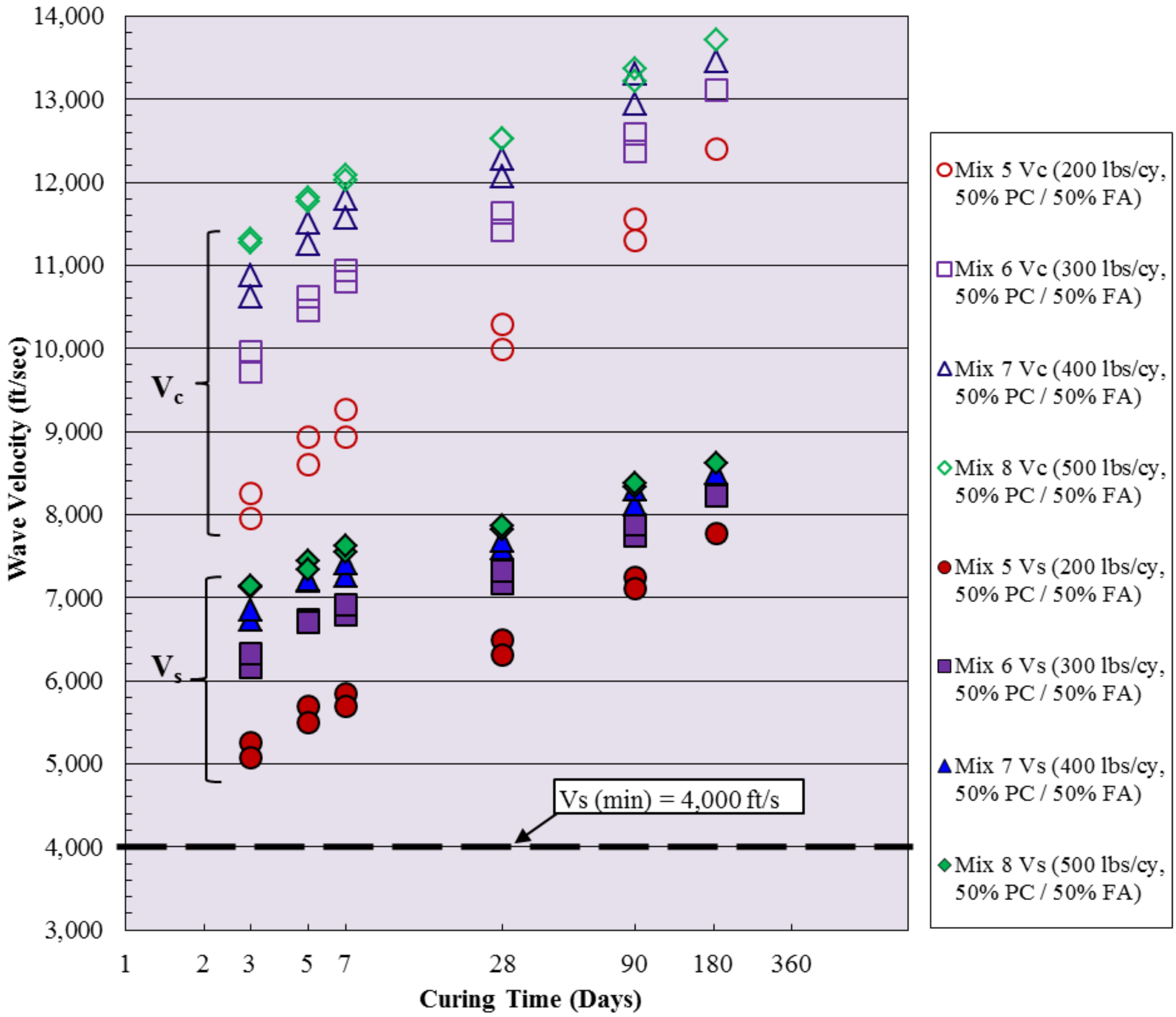

Figure 3.2 – Variation of Shear Wave Velocity (Vs) and Unconstrained Wave Velocity (Vc) with Log of Curing Time

3.3 Compressive Strength Test Results

Compressive strength tests of the MCF cylinders were completed for further characterization of concrete mix designs. For clarity, only the results of Mix Nos. 5 through 8 showing the variation of compressive strength with curing time are presented in Figure 3.3. All mixes exhibited an increase in f'_c over curing time and with corresponding increasing total cementitious content. The total cementitious content is the total cement and fly ash content proportioned for each MCF mix. As would be expected, Mix No. 5, which had the lowest total cementitious content of 200 pcy, exhibited the lowest strength at each respective curing interval, with an average 28-day compressive strength of 700 psi (4.8 MPa). Similarly, Mix No. 4, with a total cementitious content of 500 pcy, exhibited the highest strength with an average 28-day compressive strength of 4,240 psi (29.2 MPa).

The initial benefit of the fly ash is not strength gain, but its ability to improve the workability of the plastic concrete. The MCF mix designs achieved a lower w/cm ratio relative to the increasing total cementitous content, thereby resulting in increasing strength. Another benefit from fly ash is that MCF will continue, at a significant rate, to gain strength over time beyond 90 days; this phenomenon is due to the pozzalonic reaction of the fly ash with cement. The portland cement contribution occurs primarily through 90 days, but is typically about 90 percent complete at 28 days. The data trend seen in Figure 3.3 indicates that the rate of strength gain appears to be diminishing but still increasing through the curing interval of one-year. Total strength gain in mixes with appreciable quantities of fly ash can be the same or greater than those without, and this strength gain occurs over a longer period of time. The higher fly ash, lower cement content mixes have the benefit of lower heat of hydration and associated cracking.

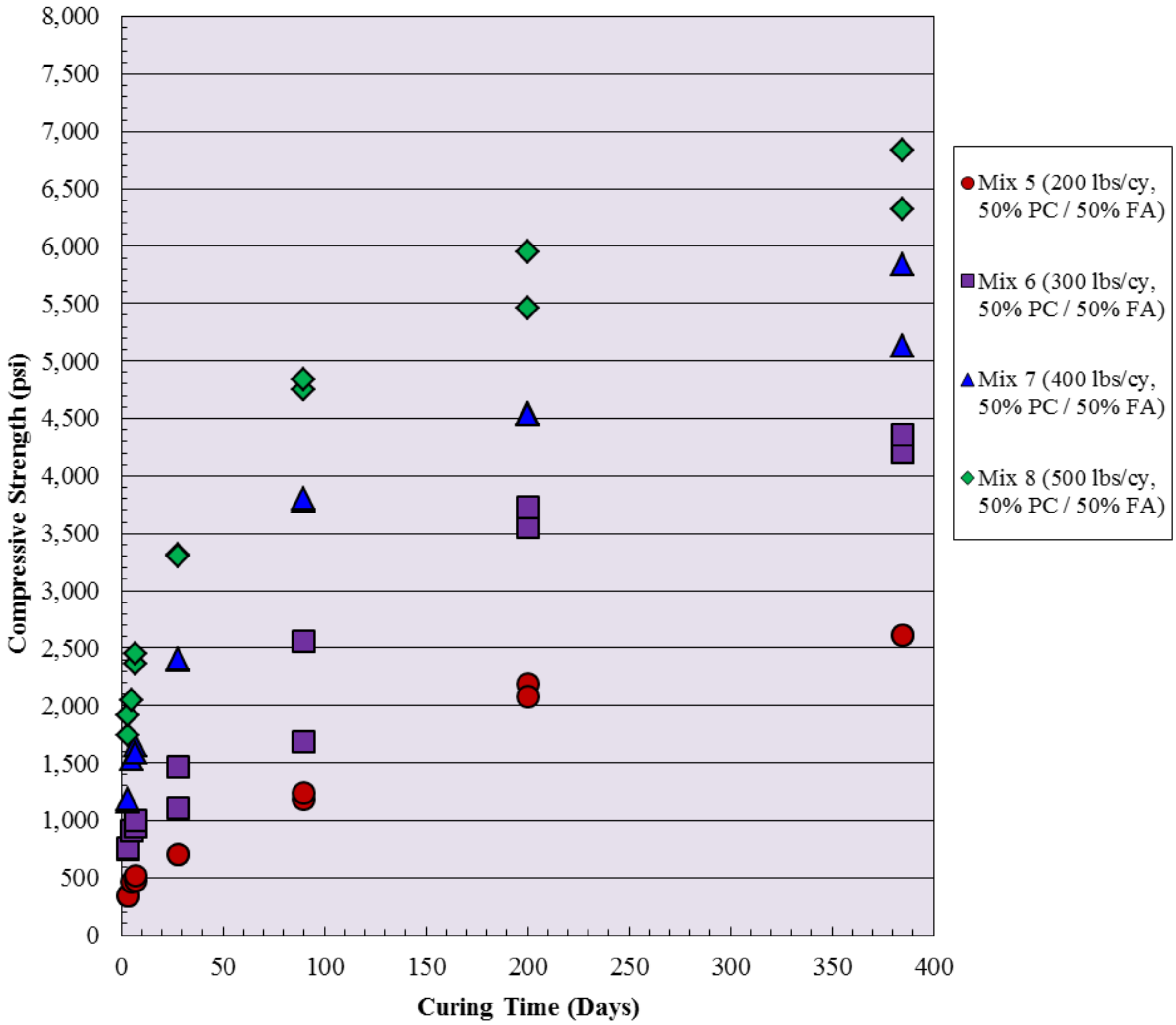

Figure 3.3 – Variation of Unconfined Compressive Strength with Curing Time

3.4 Comparative Relationship

The variation of V_s with f'_c for data points at matching curing times is presented in Figure 3.4. An exception that is included is the V_s results at the average 185 days curing time which were compared with the f'_c results at an average 200 day curing time. Both V_s and f'_c increase in value with increasing curing time, portland cement content, and total cementitious content and decrease over corresponding increases in w/cm ratio. By presenting all data points on a semi-log plot (Figure 3.4 inset), a generalized relationship was obtained for the eight MCF mixes. The V_s versus f'_c relationship of Figure 3.4 correlates very well with the trendline of Method 1, which converted data points of static E to V_s for large MCF dam sites (Figure 2.1). Methods 2 and 3 trended lower than the results of this study, but it is noted that the comparison would be improved if the 90-day f'_c data were used for correlation instead of the 28-day data.

The successful laboratory program and quality relationship will facilitate the selection of a MCF mix with acceptable dynamic properties. Other factors such as the relationship of V_s of test cylinders versus large scale MCF, which likely includes discontinuities created by heat of hydration cracking, should also be considered in the final mix selection. Due to the numerous factors contributing to this relationship of material specific MCF, caution should be exercised when extrapolating to other concrete mixes, including normal weight concrete mixes with smaller aggregate size and lower aggregate percentage (of total volume), as well as constituents with different physical characteristics.

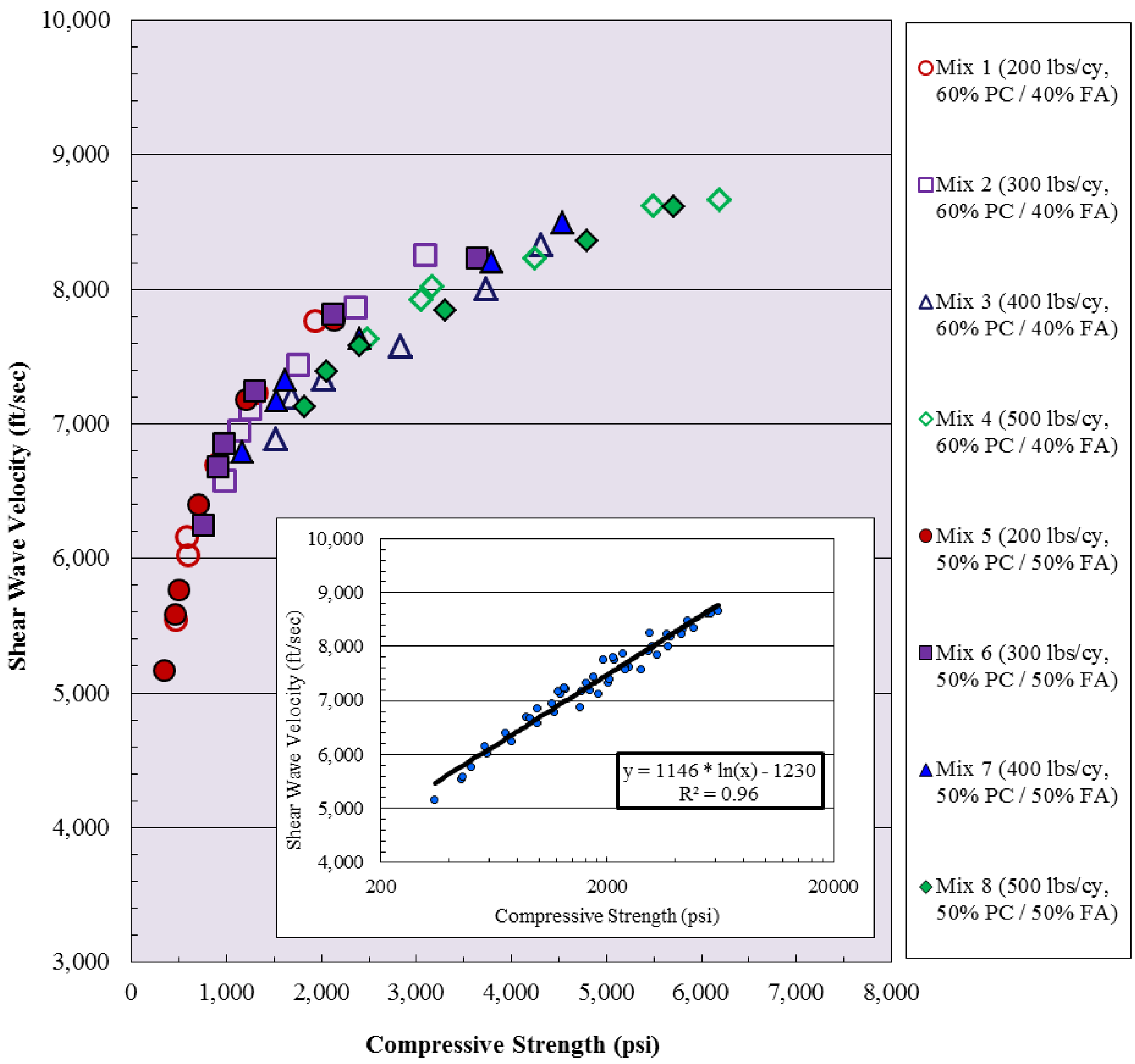

Figure 3.4 – Variation of Shear Wave Velocity with Compressive Strength

4. CONCLUSIONS

This project presents the successful use of dynamic testing in the development of MCF designs for seismic considerations. The following discussion summarizes many of the main points of the paper.

- It is possible to utilize the database of historical MCF projects with measured static properties (such as static elastic modulus and compressive strength) and translate them to a rough order of magnitude dynamic properties provided the analyst is mindful of the differences between static and dynamic tests, differences in modulus type (e.g. constrained versus unconstrained compression modulus), rate of curing, and material characteristics / blend volumes of the concrete mixes. Correlations from static modulus values (where available) are better than correlations from static compression tests.

- Dynamic testing of specific target mix designs is the most accurate method to validate target dynamic properties. Fr-Fr resonant column testing is an efficient, cost-effective, and accurate test that may be used in conjunction with compression tests of MCF cylinders to develop useful relationships of V_s and f 'c as part of a mix design program.

- The Fr-Fr tests results indicated that even MCF mixes with modest cementitious content could achieve the target V_s of 4,000 ft/sec (1,219 m/sec) within days of casting. While achieving this goal of dynamic properties is of primary importance, it is equally important to develop a mix with optimal workability that may be readily constructed during a mass concrete fill project. These are important considerations to offset the desire for lowered cement content for project cost and heat of hydration concerns.

- The concrete mix-specific relationship may also be used as part of a field quality program to verify dynamic properties and acceptable strength gain in the field at the time of construction. Non-destructive shear wave velocity measurements may be performed at the time of construction with techniques such as the Spectral-Analysis-of-Surface-Waves (SASW), as reported by Bay and Stokoe (1990).

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