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S. G. Fattal

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The effect of critical parameters on the lateral-load response characteristics of partially-grouted masonry shear walls is evaluated by conducting a synthesis of available experimental data and by utilizing a predictive equation to estimate ultimate shear strength. The results of the study indicate a need to supplement the existing data base with additional experimental and analytical research to develop an adequate basis for design of masonry shear walls. Recommendations are made on the specific areas of research to accomplish this design objective.

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The Effect of Critical Parameters on the Behavior of Partially-Grouted Masonry Shear Walls Under Lateral Loads

S. G. Fattal

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Gaithersburg, MD 20899

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Arati Prabhakar, Director

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ABSTRACT

The effect of critical parameters on lateral-load response characteristics of partially-grouted masonry shear walls is evaluated by conducting a synthesis of available experimental data and by utilizing a predictive equation to estimate ultimate shear strength. The results of the study indicate a need to supplement the existing data base with additional experimental and analytical research to develop an adequate basis for design of masonry shear walls. Recommendations are made on the specific areas of research to accomplish this design objective.

Key Words: Building technology; critical parameters; masonry; reinforced walls; shear strength; shear walls; test strength; structural design; ultimate deformations; ultimate strength.

CONTENTS

UNITS

SI units are used in this report. U.S. Customary Units are also included as a supplement to recognize the state of current masonry practices in the U.S. At the present time, masonry Codes and Standards, construction specifications and tolerances, and nominal and actual sizes of standard masonry units manufactured in the United States are all specified in U.S. Customary Units.

EXECUTIVE SUMMARY

The effect of critical parameters on the lateral load resistance of partially-grouted masonry shear walls is evaluated by analyzing available experimental data and by utilizing a predictive equation for estimating ultimate shear strength. This task is part of a series of studies to improve the state of the art in analysis and design of masonry shear walls.

The main emphasis is placed on lightly-reinforced and partially-grouted construction in areas subjected to low-to-moderate seismicity. The experimental data base is selected from 72 partially-grouted shear wall tests reported elsewhere [3]. The strength-predictive equation comes from the same source.

Chapter 4 presents the methodology and analysis of the data. It defines six major event in the lateral-load response of shear walls. The response characteristics examined are, the cracking and ultimate shear strengths and the corresponding deformations. It identifies five critical parameters based on earlier studies [2,3]: axial stress, q, the compressive strength of masonry, f'_m, aspect ratio of wall, r, horizontal reinforcement ratio, ρ_h, and, vertical reinforcement ratio ρ_v.

This chapter also discusses the effects of critical parameters ρ_h, r, q, and f'_m, based on the test results, using groups of specimens in which only one parameter varies. To complement the available test data, it examines the effects of parameters ρ_v, ρ_h, and r, calculated by Eq. (6) of Ref [3].

Chapter 5 documents the following conclusions drawn from this study: (a) strength is most sensitive in the regions of ρ_h = 0-0.2%, r = 0.5-2%, and f'_m =8-17 MPa (1.2-2.5 ksi), (b) response is approximately linear in q and ρ_v, and, (c) parametric effects on deformations can not be determined with enough certainty because of the scarcity of data points.

Chapter 6 recommends specific areas of experimental and analytical research needed to develop a rational basis for design.

1. INTRODUCTION

The NIST masonry research program includes both analytical and experimental studies of the response of masonry shear walls subjected to reversed cyclic lateral loads. It is being coordinated with studies carried out by the U.S. Technical Coordinating Committee for Masonry Research (TCCMAR) and the joint U.S.-Japan program on masonry research (JTTCMAR).

To identify research needs and priorities, available technical data on experimental research of masonry shear walls conducted since 1975 in the U.S. and abroad were reviewed. About 700 tests were identified, analyzed and classified according to type and range of test variables used in the experiments. The study was documented in a report titled "Review of Research Literature on Masonry Shear Walls" [1]. The study identified a critical need for technical information on partially-grouted and lightly-reinforced masonry shear walls suitable for construction in regions of low-to-moderate seismicity (approximately equivalent to seismic zones 1 and 2 of the 1988 Uniform Building Code (UBC)[4].

Using the findings of the literature review report as a source document, the following additional studies were carried out.

The correlation of ultimate shear strength calculated by four strength-predictive equations were compared with experimental results of 62 fully-grouted masonry walls from as many independent sources [2]. Based on these comparisons, it was concluded that none of the equations can predict the test results consistently enough to develop a credible basis for design.

A similar correlation study was carried out using a proposed strength-predictive equation with the test results of 72 partially-grouted specimens from three independent experimental programs [3]. The predictions of more than half of the specimens were outside the range of ±20% of measured strength. However, when the functional forms of the parameters within the predictive equation were altered to simulate more closely post-cracking behavior, the correlation with test results improved.

The present study identifies critical parameters that control the behavior of partially-grouted masonry shear walls. The methodology consists of a synthesis of experimental data and the use of a strength-predictive function developed as part of the study of partially-grouted walls [3]. The results are then utilized to identify specific areas of experimental research that will be needed to develop improved design guidelines for partially-grouted masonry shear walls. The methodology and analysis are presented in Chapter 4. The summary and conclusions drawn from the analysis are summarized in Chapter 5. Recommendations of specific areas of research to develop a sound basis for shear wall design are documented in Chapter 6.

2. OBJECTIVES

The study has two objectives, (1) to develop a better understanding of the relationship between critical parameters and experimentally-measured lateral load response characteristics of partially-grouted masonry shear walls, and (2) to develop a reasonable perspective on the scope of analytical and experimental research needed to improve the state of the art in the design of masonry shear walls. To formulate the research plan, a specific list of recommended research topics for partially-grouted masonry shear walls is also proposed.

3. SCOPE

The two NIST studies [2,3] are used as the primary source materials for the present study. The effect of critical parameters on ultimate load and deformation response is examined by a synthesis of the experimental data and application of the following strength-predictive equation developed in an earlier study (Equation 6, Ref. [3]):

$$
\begin{aligned}
v_p &= v_m + v_s + v_q \\
&= k_o . k_u . [(0.5/(r+0.8))+0.18] . (f'_m)^{0.5} . (f_{yv})^{0.5} . (\rho_v)^{0.7} \\
&\quad + k_o . (0.011) . (\gamma) . (\delta) . f_{yh} . (\rho_h)^{0.31} \\
&\quad + k_o . (0.012) . (f'_m) + (0.20) . (q) \ldots\ldots\ldots\ldots\ldots \text{(Eq. 6, Ref. 3)}
\end{aligned}
$$

where,

k_o = 0.8 for partially-grouted (PG) walls, and 1.0 for fully-grouted (FG) walls

f'_m = compressive strength of masonry from prism tests

f_{yh} = yield strength of horizontal reinforcement

f_{yv} = yield strength of vertical reinforcement

k_u = numerical coefficient specified according to type of masonry, type of loading and type of grouting (full or partial)

q = nominal axial stress on wall

r = aspect ratio of wall

v_u = nominal ultimate shear strength (stress units)

δ = numerical coefficient to account for the effect of boundary conditions in prediction of shear strength

λ = numerical coefficient specified according to type of masonry and type of grouting.

ρ_h = horizontal reinforcement ratio

ρ_v = vertical reinforcement ratio

For clarity, the terms designating the type of masonry construction are defined as follows:

Plain: masonry which contains no grout or reinforcing bars.

Partially-grouted: masonry in which part of the hollow cores are grouted.

Fully-grouted: masonry in which all the hollow cores are solidly grouted.

Joint-reinforced: masonry which contains joint reinforcement placed in bed joints.

Reinforced: masonry in which reinforcing bars and/or joint reinforcement is used.

Unreinforced: masonry which contains no reinforcement.

The experimental data base is assembled from the 72 tests of partially-grouted specimens [3]. The improved predictive equation is used in this study to evaluate the effect of the individual parameters on strength over a broader range of values than those used in the test specimens.

4. METHODOLOGY AND ANALYSIS

4.1 Shear Wall Response Under Lateral Load

Based on observations from past experiments, the response of masonry shear walls under lateral load may be characterized by six possible major events. These events are described below and identified in figure 1 for a wall in which the top and bottom surfaces are rotationally fixed:

(1) Horizontal tensile cracks in the wall occur at diagonally opposite corners where flexural tensile stresses are high.

(2) Yielding of flexural tensile steel occurs at the same locations.

(3) Shear (tensile) cracking occurs in the central region of the wall, approximately along the loaded diagonal, causing a redistribution of stresses to reinforcing bars across the ruptured surface.

(4) Shear cracks propagate to the loaded corners until a complete rupture plane develops, at which stage, resistance to lateral loads is provided by reinforcing bars crossing the rupture plane as well as by aggregate interlock within the high compression regions near the diagonally loaded corners.

(5) Reinforcement across the rupture plane yields in tension (horizontal bars), and in flexure (vertical bars).

(6) Crushing of masonry occurs within the high compression zones at the diagonally loaded corners.

These events do not necessarily occur in the sequence indicated. Furthermore, certain events, such as yielding of reinforcement (events 2 and/or 5) may occur partially or not at all, depending on the amount of reinforcement used, the level of axial load, aspect ratio of the wall, and other factors that will be described in the next section.

4.2 Critical Parameters

The current study uses part of the 72 partially-grouted masonry tests reported in Reference [3]: 52 tests conducted by Matsumura [5] and 10 NIST tests by Yancey et al. [6]. The 72 tests constitute about 10% of the 700 shear wall tests identified in the literature review [1]. About 60% of these tests used fully-grouted specimens, and 30% were plain walls. Data on plain and fully-grouted specimens are utilized in this study to the extent needed to supplement the information on partially-grouted specimens.

The former studies [2,3] have identified the following parameters as the major contributors to the lateral load resisting capacity of masonry shear walls.

ρ_h = Horizontal reinforcement ratio; total horizontal steel area divided by the product of height and thickness of wall

ρ_v = Vertical reinforcement ratio; total vertical steel area divided by the product of length and thickness of wall

r = Aspect ratio h/L; height divided by length of wall

q = Axial stress; axial load Q divided by gross area A defined as the product of length and thickness of wall

f'_m = Compressive strength of the masonry determined by axial load tests of prisms; axial load at failure divided by gross area of prism.

The effect of these parameters are examined against the following four response characteristics:

v_c = First diagonal cracking strength of the masonry; lateral load P_c, at first cracking, divided by gross area, A,

d_c = Deformation corresponding to first diagonal cracking load P_c; lateral displacement D_c, at P_c, divided by height h of wall,

v_u = Ultimate strength of wall; peak lateral load P_u, divided by gross area, A of wall,

d_u = Deformation corresponding to peak load P_u; lateral displacement D_u, at P_u, divided by height h, of wall.

4.3 Effect of Parameters Based on Test Results

The effects horizontal reinforcement ratio, aspect ratio, axial stress, masonry compressive strength, and vertical reinforcement ratio on the resistance of shear walls are presented in this chapter.

A. Horizontal Reinforcement Ratio

Figure 2 shows the effect of horizontal steel ratio ρ_h on ultimate strength v_u using the test results of six groups of specimens reported by Matsumura [5]. Except for ρ_h, the remaining four parameters (ρ_v, r, q, and f'_m) are essentially the same in each group, as shown in Table 1.

Figure 2 shows that the increase in strength, with ρ_h increasing from 0 to 0.22% is moderate for specimens of groups 1 and 3 (Note: in the figures, ph=ρ_h, pv=ρ_v, vu=v_u, vc=v_c, du=d_u, dc=d_c).

Table 1. Six groups of identical tests except in ρ_h, conducted by Matsumura [5].

Group	Test No.	ρ_h	f'_m	ρ_{ve}	r	q
1	7	0	1379	.00391	1.36	0
	8	0	do	do	do	do
	9	.00071	do	do	do	do
	10	.00148	do	do	do	do
	11	.00222	do	do	do	do
2	15	0	1176	.00377	1.31	71.1
	16	.00148	do	do	do	do
	17	.00222	do	do	do	do
	18	.00335	do	do	do	do
3	20	0	2264	.00391	1.36	142.2
	22	.00148	do	do	do	do
	23	.00222	do	do	do	do
4	32,33	0	1378-93	.01018	2.29	0
	34,35	.00071	do	do	do	do
5	36,37	0	1378-93	.01018	3.44	0
	38,39	.00071	1378	do	do	do
6	42	0	2351	.00717	2.22	0
	43	.00107	do	do	do	do
	44	.00222	do	do	do	do
	45	.00335	do	do	do	do

In group 6, the strength increase is significant (almost doubles) up to ρ_h = 0.22%. Increasing ρ_h to 0.34% causes the strength to decrease slightly. Overall, the maximum gain in strength occurs in the range of 0 to 0.22% reinforcement ratio. Above that range, the gain decreases with an increase in ρ_h.

For the same six groups, Figure 3 indicates that the cracking strength is not or only slightly affected by ρ_h in the range of 0 to 0.34%. A similar trend in fully-grouted walls was also noted in an earlier study [2]. This indicates that horizontal steel generally does not become structurally engaged until after shear cracking has occurred.

The only available information on deformation response was from two sets of specimens that were identical except in ρ_h (Figure 4). Because of limited test data no conclusive explanation can be given for the fact that the specimen with a ρ_h = 0.23% developed a cracking deformation four times larger than the specimen which had no horizontal reinforcement.

Figures 5 shows the effect of horizontal reinforcement on the strengths of ten specimens tested at NIST [6]. Table 2 lists the values of the five parameters r, q, f'_m, ρ_v, and ρ_h, and the ultimate shear strengths, v_t for these specimens. All the specimens except one contained horizontal reinforcement only. Specimen 63, which was a plain unreinforced wall (see definitions, Section 3), was the exception. The test variables were the amount, distribution, and type of horizontal reinforcement. Specimens 64 and 65 contained only light joint reinforcement in every other course and in every course, respectively (they were plain joint-reinforced walls according to the definitions in Section 3). Specimens 68 and 72 were duplicates, so were specimens 67 and 69.

In general, horizontal reinforcement ratio of up to 0.1% causes both ultimate and cracking strengths to increase. Beyond that level, its effect is uncertain.

The results in Figure 5 indicate that joint reinforcement of equivalent area may be as effective as deformed rebars in improving response. This trend becomes evident by comparing the results of specimens 64 and 65, which were only joint-reinforced, with duplicate specimens 68 and 72, which contained only horizontal rebars. Also note that the gain in ultimate strength of specimen 70 (in which joint reinforcement accounted for about half of the total reinforcement), relative to specimen 63 (which was unreinforced), is in line with the ultimate strength of specimen 66 which contained only rebars but had about twice the amount of reinforcement in specimen 70. This finding can have a positive economic implication for the masonry industry because joint reinforcement eliminates the need for grouting, a costly alternative when horizontal rebars are used.

Figure 6 shows that both the ultimate and cracking deformations increase with increasing horizontal reinforcement ratio of up to 0.2%. Specimens 67 and 69, which contained maximum reinforcement, did not follow the same trend. They developed lower strengths and lower corresponding deformations.

The NIST test results give no indication of whether the location or distribution pattern of horizontal reinforcement within the wall has any effect on response. For instance, the deformations of specimens 68 and 72, in which bars were placed at two locations (at one- and two-thirds height, approximately), show no meaningful difference from the results of specimens 66, 67, and 69, in which bars were placed at mid-height only.

Table 2. Selected data from NIST tests of horizontally-reinforces specimens, by Yancey et al. [6].

TEST	r	q	f'_m	ρ_{ve}	ρ_h	v_t
63	1.2	107	1292	0	0	70
64	1.2	107	1230	0	.00023	87
65	1.2	107	1112	0	.00047	89
66	1.2	107	1217	0	.00094	120
67	1.2	107	1263	0	.00218	92
68	1.2	107	1087	0	.00072	98
69	1.2	107	1242	0	.00218	73
70	1.2	107	1095	0	.00050	103
71	1.2	107	856	0	.00213	121
72	1.2	107	1070	0	.00073	98

In summary, the results from Matsumura's and NIST tests indicate that the effectiveness of horizontal reinforcement above 0.2% is questionable. The conclusions drawn from the results of 32 fully-grouted masonry tests conducted at Berkeley by Sveinsson et al. [7] provide partial confirmation of this trend. The authors note that "typically, improvement can be expected for horizontal reinforcement ratios of up to three to five times the minimum ratio specified by the 1985 UBC (0.07%)". The lower ratio 3x0.07%= 0.21% is in agreement with the findings of this study. Note that horizontal reinforcement ratios of the partially-grouted specimens in this study are based on the same gross vertical area of the specimens (height times thickness) as that used for the fully-grouted specimens.

B. Aspect Ratio

Several investigators have examined the effect of aspect ratio on the behavior of fully-grouted masonry walls [8, 9, 10]. By comparison, studies of the effect of aspect ratio for partially-grouted walls is limited to the tests conducted by Matsumura [5].

Figure 7 shows the effect of aspect ratio r, on the ultimate strength of six groups of partially-grouted specimens tested by Matsumura [5]. The values of the parameters are specified in Table 3. The figure indicates that ultimate strength is not very sensitive to aspect ratios greater than 2. As aspect ratio decreases, its effect on ultimate strength increases at an increasing rate for groups 5 and 6 in which specimens of aspect ratio of 0.75 developed more than twice the ultimate strength of specimens having an aspect ratio of 2.25. For groups 1 and 4, the increase is moderate.

Figure 8 shows the influence of aspect ratio on the cracking strength of the same six groups of specimens. The trend is less pronounced but somewhat similar, assuming the low cracking strength of the specimen having an aspect ratio of 1.5 in group 5 can be discounted because it exceeds the scatter shown for the rest of the data points.

Figure 9 shows that the aspect ratio has almost no or a slight effect on ultimate and cracking shear deformations. Additional data points will be needed before definite conclusions can be drawn on the nature of this relationship.

Figures 10 and 11 show the effect of aspect ratio on plain masonry walls reported by Woodward and Rankin [11]. The downward trend of ultimate strength with increasing aspect ratio is consistent with Matsumura's results. The results of the effect of aspect ratio on ultimate deformations (Figure 11), are too erratic to interpret.

C. Axial Stress

Depending on its magnitude, axial load can have a positive or negative effect on response. It delays formation of horizontal tensile cracks in flexure at the diagonally-opposite unloaded corners (event 1 in Fig. 1), yielding of steel in flexure (event 2), and formation of diagonal shear cracks at the center of the panel (event 3). Thus complete rupture (event 4) will occur under a higher lateral load than if axial load were low or not present. However, a large axial load may trigger a premature crushing at the diagonally-loaded corners because it takes away part of the capacity of masonry to resist compression in flexure. Thus it reduces the incremental load between events 1 and 4.

Table 3. Six groups of identical tests except in aspect ratio r, conducted by Matsumura [5].

Group	Test No.	r	f'_m	ρ_{ve}	ρ_h	q
1	2	1.05	2264	.00370	.00071	0
	4	1.36	do	.00357	do	do
	6	1.96	do	.00367	do	do
2	30,31	1.13	1379-93	.01018	0	0
	32,33	2.29	do	do	do	do
	36,37	3.44	1393	do	do	do
3	34,35	2.29	1379-93	.01018	.00071	0
	38,39	3.44	1379	do	do	do
4	24,25	.914	1277	.00261	.00148	71.1
	26	1.02	do	.00242	do	do
	27	1.31	do	.00247	do	do
	28,29	1.86	do	.00266	do	do
5	46	0.75	2772	.00845	.00107	0
	48	1.50	do	do	do	do
	50	2.25	do	do	do	do
6	47	0.75	3556	.00845	.00107	0
	49	1.50	do	do	do	do
	51	2.25	4383	do	do	do

The case of zero axial load deserves to be studied further. A substantial portion of masonry elements in buildings, including partitions and those in existing buildings which have been retrofitted, do not experience axial load in service.

The effect of axial load on plain and fully-grouted walls have been investigated quite extensively in the past [1]. The effect of zero axial load on the response of partially-grouted walls, however, has not been sufficiently investigated.

Figure 12 shows the results of an investigation of axial load effects on plain walls by Woodward and Rankin [12], and on partially-grouted walls by Matsumura [5]. The five critical parameters for these two sets of walls are specified in Table 4.

Approximation of axial load effects by a linear function yields the regression equations

$$v_u = 0.205 + 0.393q \quad \text{(MPa)}$$

$$v_u = 29.73 + 0.393q \quad \text{(psi)}$$

for the plain walls, and

$$v_u = 0.584 + 0.196q \quad \text{(MPa)}$$

$$v_u = 84.69 + 0.196q \quad \text{(psi)}$$

for the partially-grouted walls.

Noting that the two groups are not appreciably different in f'_m and r (Table 4), the difference in strength between partially-grouted and plain walls under zero axial load (the first terms in the above equations) reflects mainly the effect of reinforcement. According to the above results, the strength of plain walls is about twice as sensitive to axial load compared to the strength of partially-grouted walls (coefficient of q in the above equations).

The only available data on the effect of axial load on deformation at ultimate load are those reported by Woodward and Rankin [11] for plain walls. According to figure 13, the relationship appears to be approximately linear and the deformation at ultimate load in plain walls increases by about 50% as axial stress varies from 0.55 to 1.79 MPa (80 to 260 psi).

Table 4. Groups of specimens having common properties except in axial stress q.

Group	Test No.	q	r	f'_m	ρ_{ve}	ρ_h
			MATSUMURA'S TESTS			
1	4	0	1.36	2264	0.00357	0.00071
	12	71	do	do	do	do
	13	142	do	do	do	do
	14	213	do	do	do	do
			TESTS BY WOODWARD ET AL.			
1	CB2	82	1.00	1820	0	0
	CB3	123	do	2132	do	do
	CB4	154	do	1870	do	do
	CB5	164	do	2091	do	do
	CB6	205	do	2810	do	do
	CB7	205	do	2074	do	do
	CB8	256	do	2005	do	do

D. Compressive Strength of Masonry

Test data on the effect of the masonry compressive strength on the response of partially-grouted shear walls are limited. Figure 14 was developed from Matsumura's test data for the groups listed in Table 5 [5]. Three pairs of curves are shown. The top and bottom curves in each pair correspond to ultimate and cracking shear strengths, respectively. The plots for the four fully-grouted specimens do not exhibit a distinct trend. Further tests are needed to clarify the effect of higher compressive strengths (≥ 20 MPa or 3000 psi) on cracking and ultimate strengths. The lowest pair of curves indicates that within the lower ranges, cracking and ultimate shear strengths may be quite sensitive to compressive strength. Most of the recent NIST tests of concrete block shear walls [3,11,12] fall within this range (8.3 to 17.3 MPa or 1200 to 2500 psi).

Table 5. Groups of specimens having common properties except in f'_m

Group	Test No.	f'_m	q	r	ρ_{ve}	ρ_h
		<u>MATSUMURA'S TESTS (PG WALLS)</u>				
1	21	1176	142	1.36	0.00391	0.0
	20	2264	do	do	do	do
2	40	2351	0	1.21	0.00391	0.00107
	41	2554	do	do	do	do
		<u>MATSUMURA'S TESTS (FG WALLS)</u>				
1	18	3232	284	1.51	0.00448	0.00334
	21	3782	do	do	do	do
	20	4203	do	do	do	do
	24	4551	do	do	do	do

E. Vertical Reinforcement

In experimental investigations of the shear capacity of partially-grouted masonry walls, one of the attributes is the amount and distribution of vertical reinforcement. The amount of vertical reinforcement is the first parameter to consider in the design of test specimens. For an assumed set of parameters, r, q, ρ_h and f'_m, the amount of vertical reinforcement is established as follows: (a) select ρ_v, (b) estimate its shear capacity by analysis, (c) check for flexure to make sure its flexural capacity exceeds its shear capacity. Otherwise, increase ρ_v to make sure that it does.

Flexural capacity can be checked by established flexure theory. The shear capacity may be estimated by using a predictive equation such as Equation (6) of Ref. [3].

The effect of vertical reinforcement in partially-grouted walls has not been investigated experimentally. The 52 specimens tested by Matsumura used varying amounts of vertical reinforcement in the outer cores, but did not include any subgroups in which only vertical reinforcement was varied. In Section 4.4, the effect of several vertical reinforcement ratios in combination with other parameters is examined using Equation (6).

F. Summary and Conclusions

The following conclusions are drawn from the study of parametric effects subject to the limitations of available experimental data base.

1. Ultimate strength and ultimate deformation increase with increasing horizontal reinforcement ratio within the range of 0 to 0.2%. Horizontal reinforcement above 0.2% shows little or no effect on either property. To a lesser extent, this observation applies to the cracking strength and cracking deformation (Figures 2-6).

2. Within the range examined, the effect of joint reinforcement on response is comparable to that of horizontal reinforcing bars of comparable area.

3. Aspect ratios greater than 2 have virtually no effect on strength (Figure 7). As aspect ratio is reduced below 2, both ultimate and cracking strengths increase at an increasing rate, the most substantial increase occurring between r = 1.5 and 0.75 (Figure 7). Aspect ratio has almost no effect on deformations within the range of r = 0.75 to 3.5 (Figure 9).

4. Within the limits used in the tests (0 to 1.8 MPa or 0 to 260 psi), ultimate strength increases linearly with increasing axial stress (Figure 12). The relationship is described approximately by an equation of the form $v_u = a + bq$, in which b = 0.2 and 0.4 for partially-grouted and plain walls, respectively, and the value of a (strength at zero axial load) depends on the other four critical parameters. Available information on plain walls indicates an approximately linear increase in deformation at ultimate load with increasing axial load in the range of 0.55 to 0.99 MPa, or 80 to 260 psi (Figure 13).

5. Information on the effect of masonry compressive strength for partially-grouted walls is scarce. The only available information (two data points) indicates increasing f'_m from 8.28 to 17.25 MPa (1200 to 2500 psi) doubles both the cracking and ultimate strengths.

4.4 Prediction of Parametric Effects

In Section 4.3, the effect of critical parameters on strength and deformation properties of partially-grouted masonry walls was evaluated using available test results. In this Section, Equation (6) of Reference [3] (reproduced in Chapter 3) is applied to evaluate the effect of key parameters on ultimate strength. The ability of the function to correlate with test results was demonstrated in the earlier study [3].

The specific values assigned to these parameters in the current evaluation extends beyond the range for which test results are available. The purpose is to develop a better feel for the regions in which ultimate strength is most sensitive to variations in these parameters.

Based on the observations in Section 4.3, low and high values for the compressive strength and axial stress are selected as follows:

f'_m = 10.35 and 17.25 MPa (1500 & 2500 psi), q = 1.04 & 1.73 MPa (150 & 250 psi). The effect of vertical reinforcement is examined first, with known (fixed) values assigned to the other parameters. Successive parameters are then varied and fixed, one at a time.

A. Effect of Vertical Reinforcement

Assume the following values for all the examples that follow:

k_u = 0.60, γ = 0.64, and f_y = 345 MPa (50,000 psi)

Assume the following design combinations:

	1	2	3	4	5
	ρ_v	ρ_h	r	q	f'_m
1	0.0020	0.0005	1.00	1.04(150)	10.35(1500)
2	0.0025	0.0010	0.75	1.73(250)	17.25(2500)
3	0.0030				
4	0.0040				
5	0.0050				
6	0.0060				

The design on row 1 in the above matrix is used as datum for all the other designs. There are altogether 30 designs in which four parameters (other that ρ_v) are varied once, and the one parameter, ρ_v, is varied five times (total of six ρ_v's). The designs are divided into five groups (v_1 through v_5) with six specimens in each. Each group contains four fixed elements and one variable element, ρ_v. For example, group v_1 consists of six designs as follows. The first design combines matrix elements 1-1, 1-2, 1-3, 1-4, and 1-5; The second combines elements 2-1, 1-2, 1-3, 1-4, and 1-5; the third combines elements 3-1, 1-2, 1-3, 1-4, and 1-5, and so on. The first design of group v_2 contains the elements 1-1, 2-2, 1-3, 1-4 and 1-5, the second contains elements 2-1, 2-2, 1-3, 1-4, and 1-5, and so on.

Figure 15 shows the effect of ρ_v on the predicted strength. Note that in all cases the ultimate strength increases by about 25% when ρ_v increases from 0.002 to 0.006. Also note that the curves are nearly straight, which means the sensitivity does not vary.

Using, in turn, the values of the 'fixed' parameters in the second row of the matrix, allows one to assess their effect on strength. Thus, the higher values of q and f'_m (in the second row) results in a strength increase of about 17% (groups v_4 and v_5) relative to group v_1 (the datum). Likewise, the values of r and ρ_h in the second row cause the strength to increase by about 5% only (Groups v_2 and v_3). An additional group, v_6, combines ρ_v with all the parameters in the second row to yield the maximum increase in response,which is about 50% higher than the datum (Group v_1).

At this point the selection of an appropriate value of ρ_v for the test specimens may be addressed. The above exercise is not of much help because sensitivity is constant (the correlation is linear) and no test data are available to indicate the effect of vertical reinforcement on deformation characteristics. There seems to be little doubt that vertical bars are needed in the outer cores to resist flexure and post-cracking shear through dowel action (as shear keys). This means that the outer cores will have to be grouted.

From an economic standpoint, the cost of grouting can be high. Therefore, placement of vertical bars in the interior of the wall is ruled out (industry will not buy it). Once the decision is made to use rebars in the outer cores, the size of the rebar becomes economically irrelevant compared to the cost of grouting. In light of these factors, it would seem logical to select a sufficient amount of vertical reinforcement to preclude premature flexural failure (around ρ_v = 0.004), and keep it constant for all the specimens. In other words, eliminate ρ_v as a test variable and, at the same time, insure against premature flexural failure, and provide more capacity to resist post-cracking shear.

B. Effect of Horizontal Reinforcement

Assume the following design combinations:

	1	2	3	4	5
	ρ_v	ρ_h	r	q	f'_m
1	0.0020	0.0000	1.00	1.04(150)	10.35(1500)
2	0.0030	0.0005	0.75	1.73(250)	17.25(2500)
3		0.0010			
4		0.0015			
5		0.0020			
6		0.0025			
7		0.0030			

Figure 16 shows the effect of varying ρ_h on predicted ultimate strength. The characteristics of these curves is similar to that obtained from tests, as shown in Figure 2. That is, the strength becomes less sensitive with increasing ρ_h. By varying ρ_h from 0.0005 to 0.003% strength increases by 23% (about the same rate as vertical reinforcement). The effect of using high and low values of r and ρ_v is not significant (groups H_1-H_3). The maximum increase in strength occurs for combinations of the higher values of q and f'_m (groups H_4 and H_5).

In light of these results, it seems reasonable to treat horizontal reinforcement as a test variable. Four different horizontal reinforcement ratios in the more sensitive region should be used. The lowest practical amount (0.05%), together with zero reinforcement, should be adopted to study the transition between plain and reinforced masonry. The upper limit should be set at 0.2% because horizontal reinforcement loses its effectiveness beyond that level. A fourth ratio between 0.05% and 0.2%, should be considered. With an additional data point, it will be possible to establish the correlation between ρ_h and response limit states more accurately.

According to the NIST test results (Figures 5 and 6 and [6]) the distribution of horizontal reinforcement has no discernible effect on response. Therefore, a study of the effect of distributing vs. clustering horizontal bars near mid-height does not seem warranted. Rather, grouting costs and the existence of critical tensile stresses in the central portion of the wall should guide the placement of horizontal bars in the wall. Lighter reinforcement can be placed at midheight. If needed, additional reinforcement may be placed in adjacent courses.

A most significant finding of the study is the observation that joint reinforcement is as effective as horizontal rebars in improving the response characteristics of the wall. It is strongly recommended that a set of identical pairs of specimens, one built with joint reinforcement and the other with conventional steel rebars, be included in future testing programs. Substantial savings in construction costs can be realized by using joint reinforcement placed in mortar beds and anchored to the vertical bars at the ends, in lieu of horizontal rebars place in grouted bond beams.

C. Effect of Aspect Ratio

Assume the following design combinations:

	1	2	3	4	5
	ρ_v	ρ_h	r	q	f'_m
1	0.002	0.0005	3.00	1.04(150)	10.35(1500)
2	0.003	0.0010	2.00	1.73(250)	17.25(2500)
3			1.50		
4			1.00		
5			0.75		
6			0.50		

The results for the 30 design combinations are shown in figure 17. They are consistent with the general trend of test results shown in Figure 7. However, according to Figure 17, the change in the rate of decrease in strength, particularly in the region r = 0.75 to 1.50, is more gradual.

The bottom curve (group R_1) represents combinations of r with the lower values of the other parameters listed above. Using the higher values of q and f'_m results in the highest strength increase (groups R_4 and R_5), while the strength increase for the higher value of ρ_v is minimal (group R_2).

Relatively little experimental information is available on the behavior of shallow walls (r less than 1) under lateral load. The limited available information indicates that the characteristic failure modes of shallow walls may be quite different from those having aspect ratios of 1 or greater (debonding or slipping failures rather than cracking across the mortar joint [8]). The non-linear relation between aspect ratio and strength would suggest using specimens with three different aspect ratios to develop a better grasp of their behavioral differences under lateral load.

D. Summary

In summary, the strength predictive equation offered a means by which parametric effects on ultimate strength can be estimated beyond the range of variables for which experimental data are available. Within-range agreement between measurements and predictions gives a degree of assurance that out-of-range predictions should also be acceptable.

Three parameters, ρ_v, ρ_h, and r, were examined. The effects of ρ_h and r were similar to those based on the test results: strength increases at a decreasing rate with increasing ρ_h, and increases at an increasing rate with decreasing r. Strength becomes relatively insensitive to ρ_h and r above 0.2% and 2.5, respectively.

The effect of ρ_v was estimated because no test data are available. Strength increases by 25% between the limits $\rho_v = 0.002$ and 0.006. The correlation is almost linear, which means sensitivity does not vary. Vertical reinforcement is needed in the outer cores to resist flexure and provide anchorage for horizontal bars. The use of vertical reinforcement as a test variable is ruled out because the amount of vertical reinforcement has negligible impact on construction costs.

The effect of axial load and compressive strength of masonry have been investigated extensively for fully-grouted and plain walls. It may be possible to develop a better feel for their effects on the response of partially-grouted walls by analyzing the more prolific source of information available on fully-grouted and plain walls. A test program should preferably incorporate two values of each parameter, high and low values of q and f'_m in the range of those most commonly encountered in practice. The lower limit of axial load should preferably be set at $q = 0$ (the default case) in consideration of a most-commonly encountered condition in masonry construction.

5. SUMMARY AND CONCLUSIONS

The effect of key parameters on the lateral-load response of partially-grouted masonry walls was evaluated on the basis of experimental results and a strength-predictive equation to identify research needs and priorities. The observations parametric effects, particularly on deformations, are subject to the statistical limitations of the experimental data base examined. The conclusions drawn from the current study are as follows.

Response is most sensitive within the following range of values of key parameters: $\rho_h = 0\text{-}2\%$, $r = 2\text{-}0.5\%$, and $f'_m = 8.28\text{-}17.25$ MPa

(1200-2500 psi). Within these regions, ultimate strength increases by about 50-100%, 70-100%, and 150%, respectively.

Sensitivity of strength to ρ_v and q is approximately constant. Tripling ρ_v causes a 25% increase in ultimate strength. The response to q is characterized by the linear relation $v_u = a + bq$.

Information on deformation response is scarce. Where available, deformation response within the sensitive regions of ρ_h, r, and f'_m, other than cracking deformations, exhibit a trend similar to ultimate load response. Cracking deformations are relatively insensitive to the critical parameters.

6. RECOMMENDATIONS

By utilizing the results of some of the 72 partially-grouted shear wall tests, the present study brought into focus specific areas of research needed to develop a rational design procedure for partially-grouted masonry shear walls. The following recommendations lay out the groundwork for a specific research plan.

6.1 Experimental Research

The effect of horizontal reinforcement on response should be measured in the sensitive range of ρ_h = 0 to 0.2%. Preferably four ratios should be used, including the default case of $\rho_h = 0$.

The effect of joint reinforcement on response should be investigated using at least two sizes comparable in cross-sectional area to the horizontal rebars used in other specimens.

Specimens having at least two, preferably three, aspect ratios in the range r = 0.5 to 2.0 should be tested.

Two types of masonry construction, using hollow concrete block, and hollow clay brick units, should be tested.

Two axial stress levels should be considered. One should be the default case of zero axial load; the other should be comparable to design axial stresses on masonry bearing walls in buildings.

Two compressive strengths should be investigated. This will follow automatically when the two types of masonry are included in the program.

The amount of vertical reinforcement in the outer cores should be determined by flexural considerations in a manner to prevent premature flexural failure.

Companion wallettes should be tested in diagonal compression to determine the shear cracking strength of the masonry.

Cyclic displacement-controlled tests consistent with recent research practice should be specified.

6.2 Analytical Research

The analytical work should consist of two parallel tasks. The first task is to develop formulations that can predict response properties needed in design, namely, cracking and ultimate strengths and their corresponding deformations. These formulations should evolve from observed resistance phenomena and be verified against measurements for validation. The second task is to predict response envelopes based on discrete finite element models and their validation against test results.

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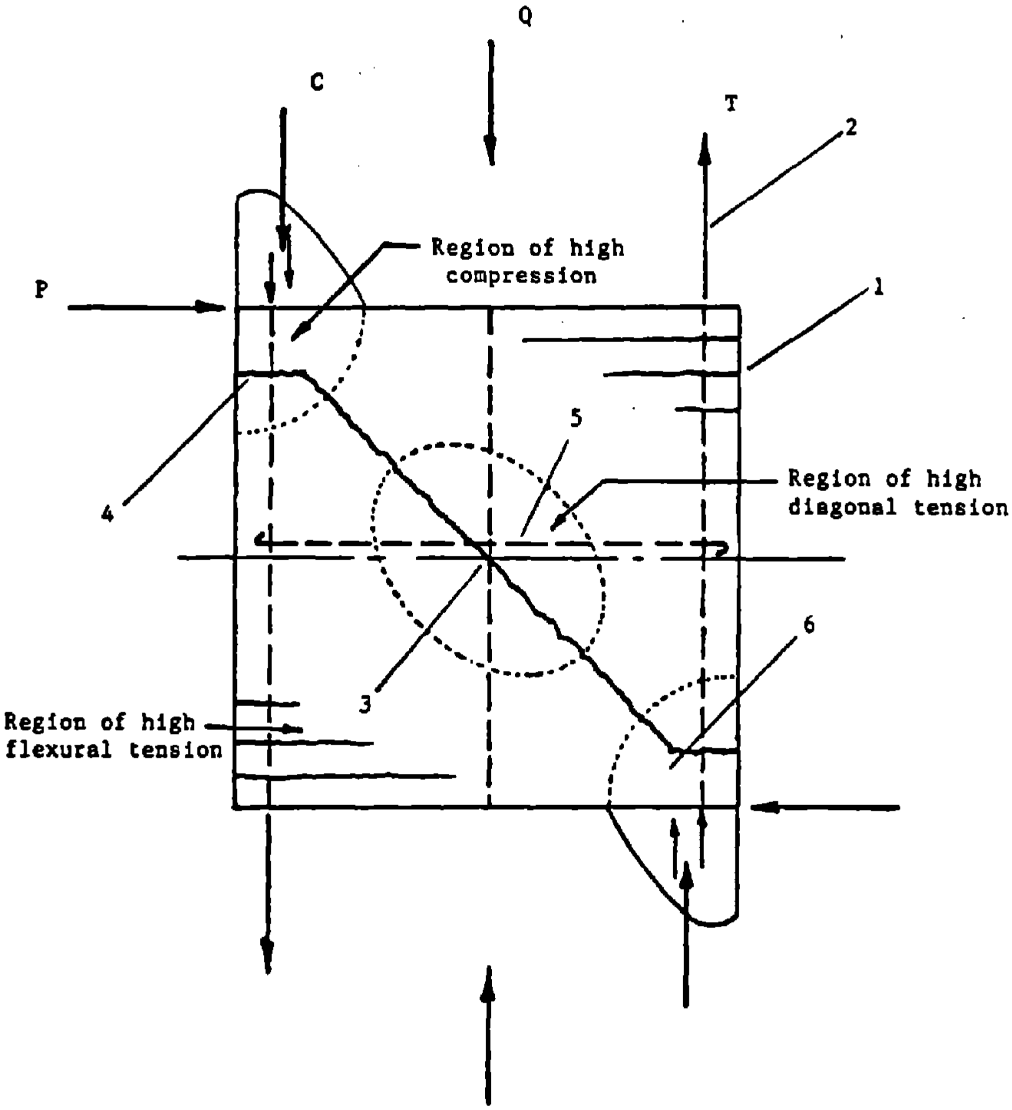

1. Tensile cracking in high flexure zones

2. Vertical bars yield in high flexure zones

3. Tensile shear-induced cracking near center of wall

4. shear cracks propagate to form rupture plane

5. yielding of hor. and vert. steel

6. crushing of masonry in compression at loaded corners

Figure 1. Major events in shear wall response

Figure 2. Effect of ph on vu

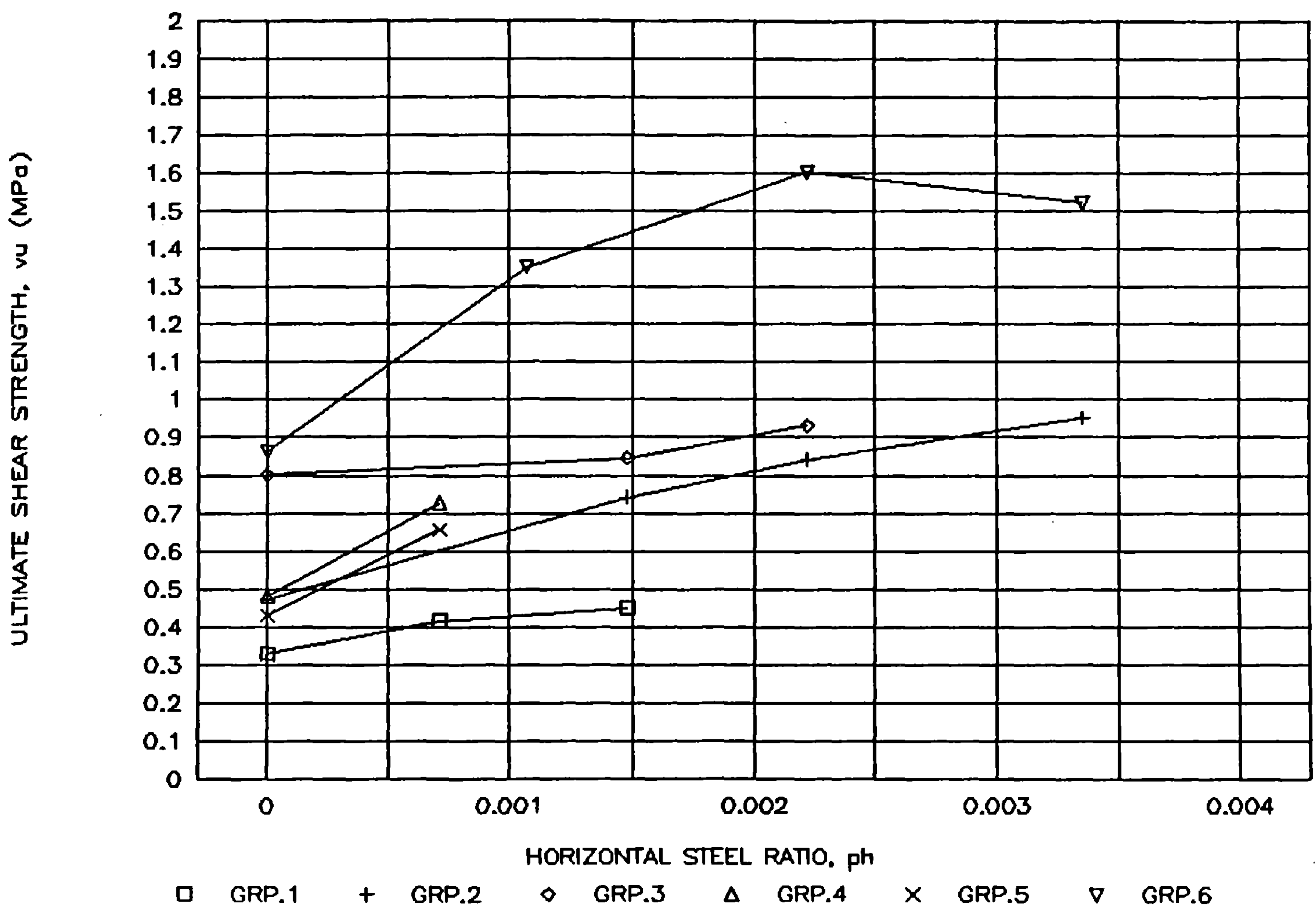

Figure 3. Effect of ph on vc

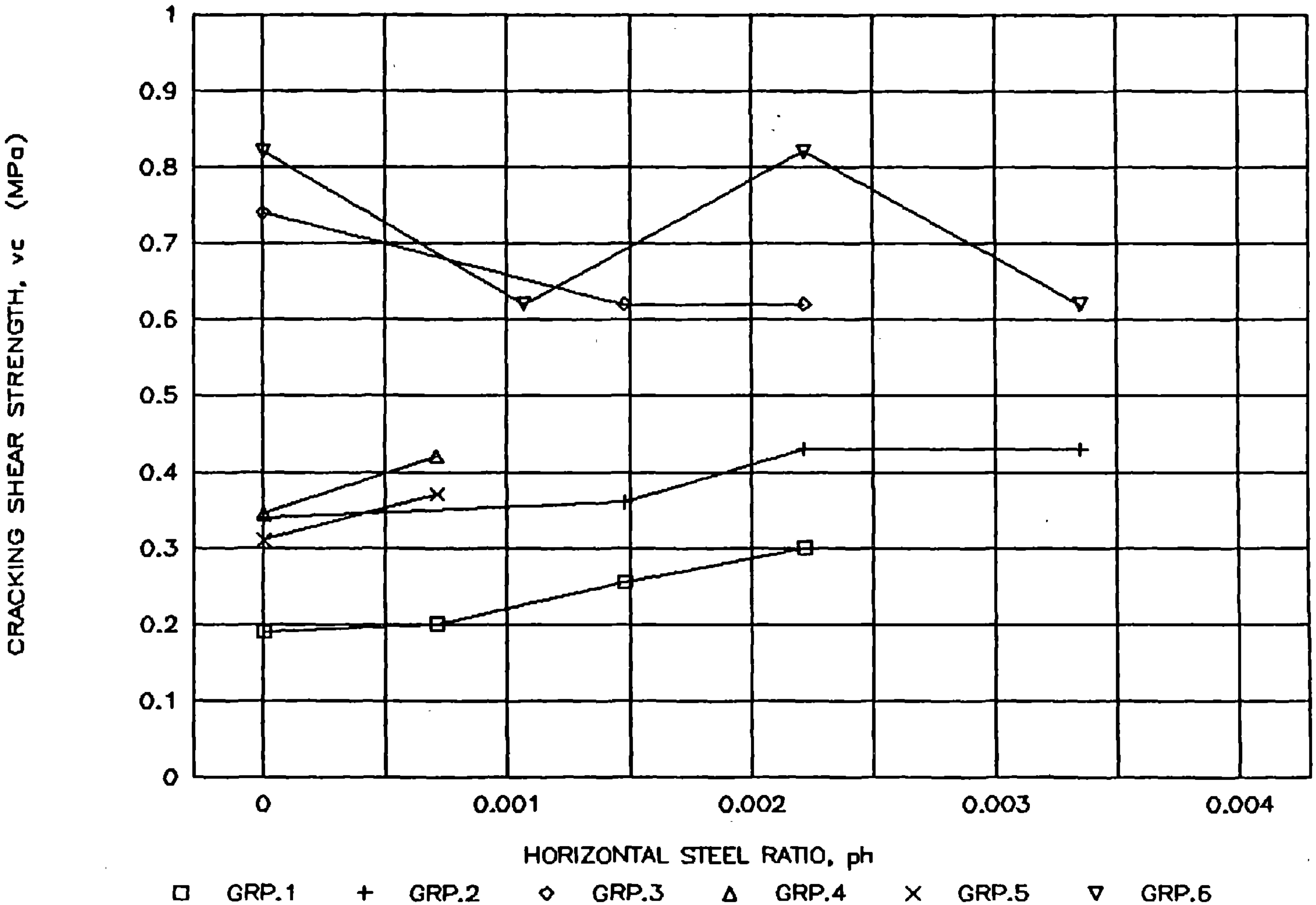

Figure 4. Effect of ph on du and dc

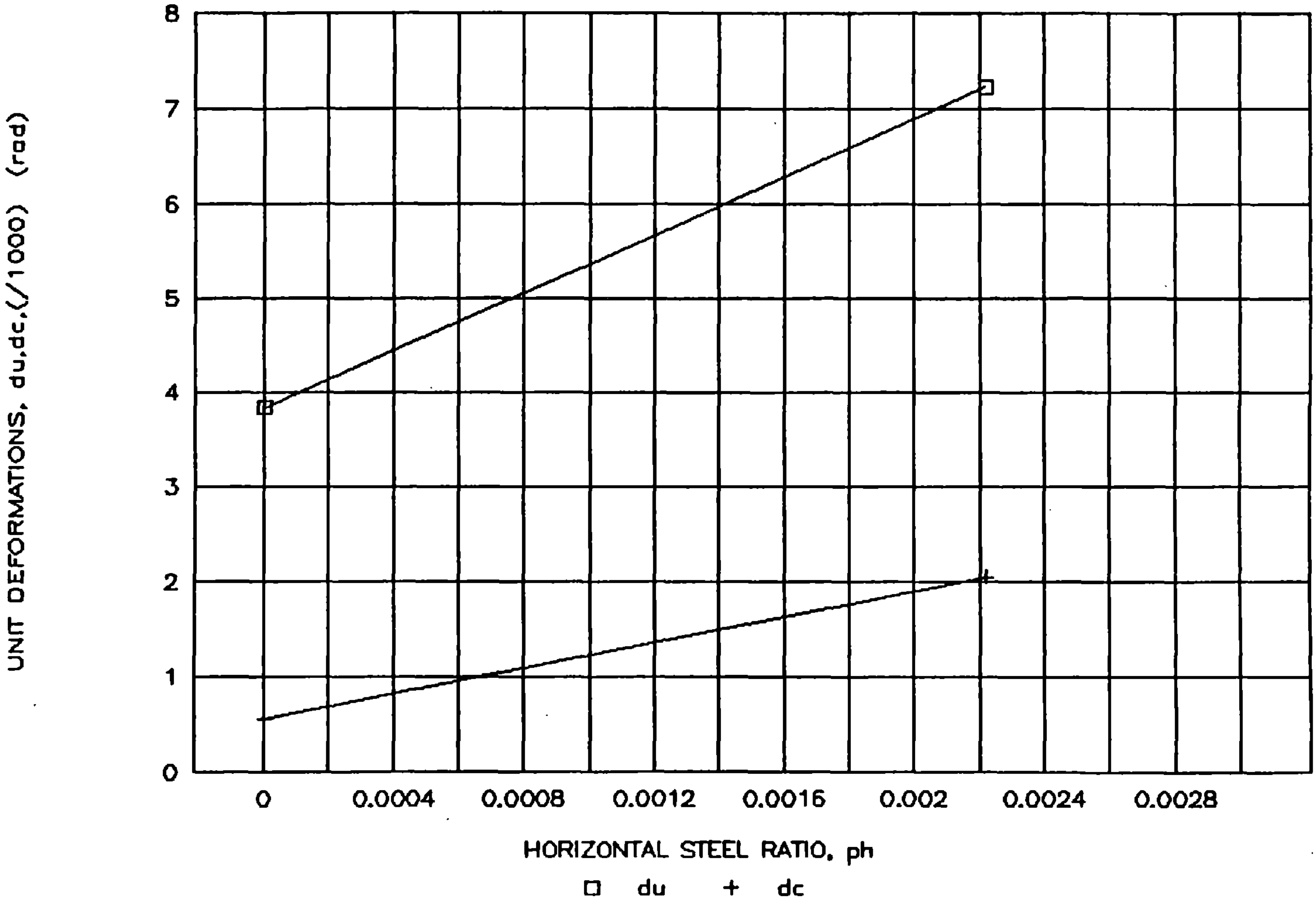

Fig. 5. Effect of ph on vu and vc

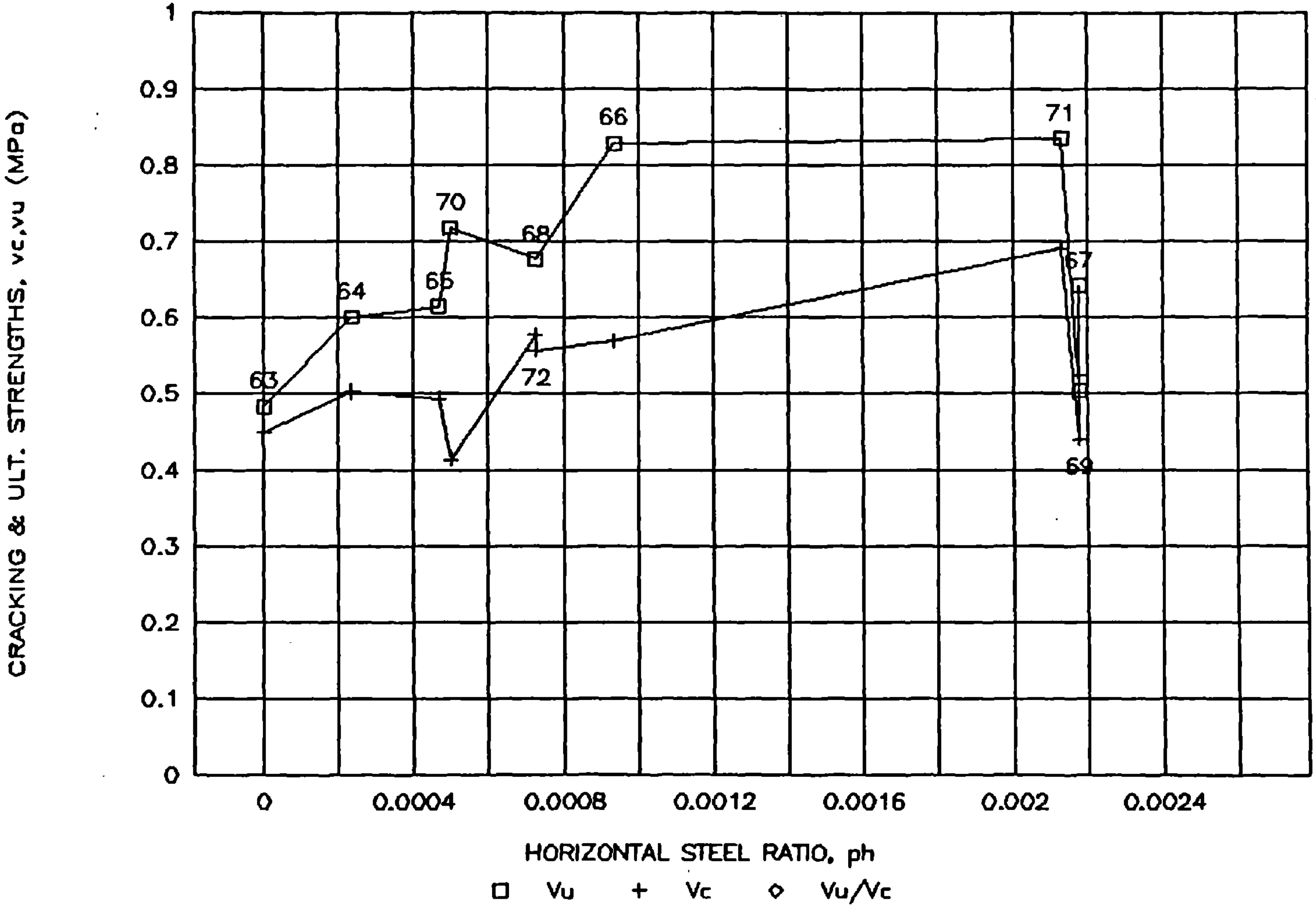

Figure 6. Effect of ph on dc and du

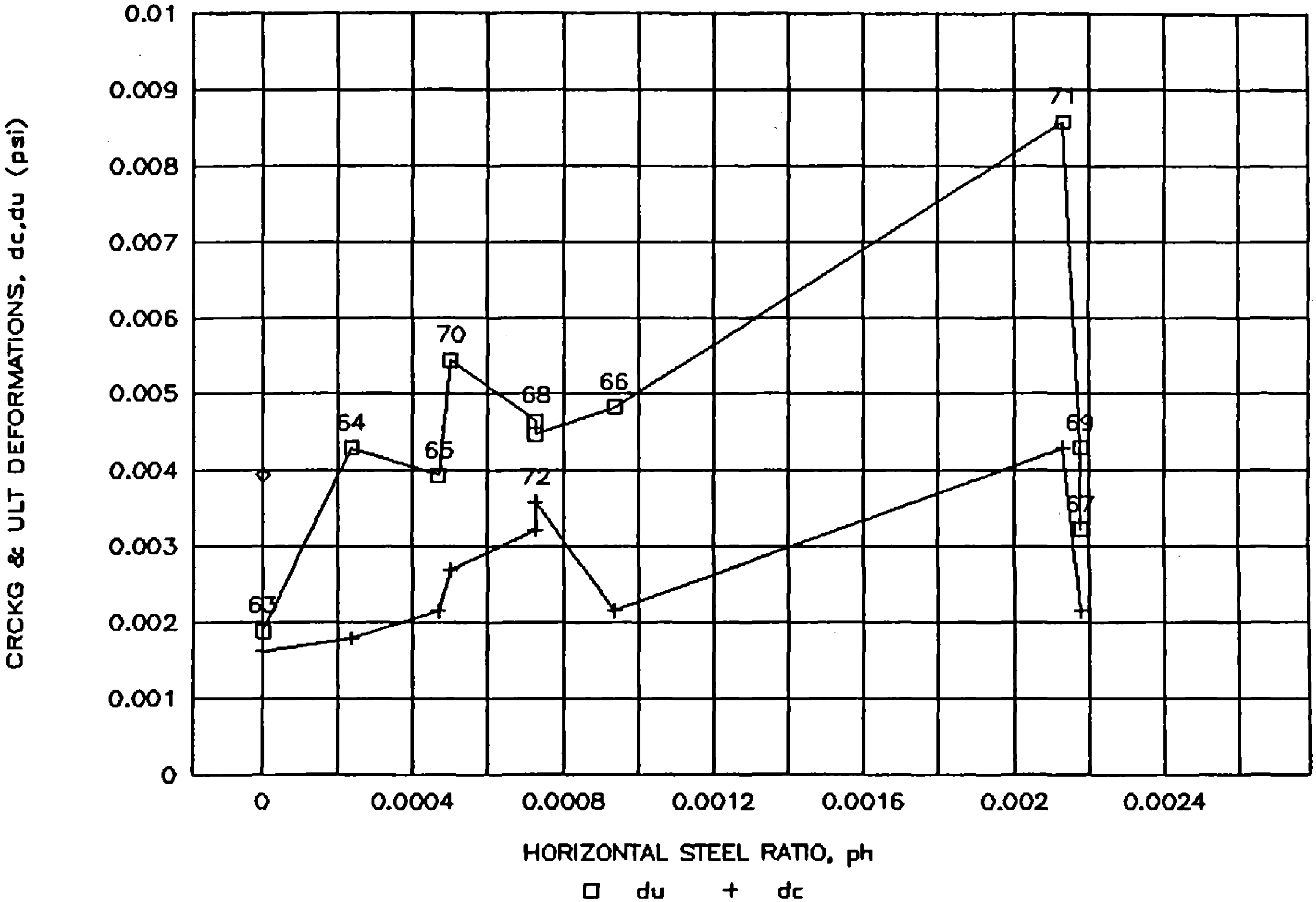

Fig. 7. Effect of r on vu

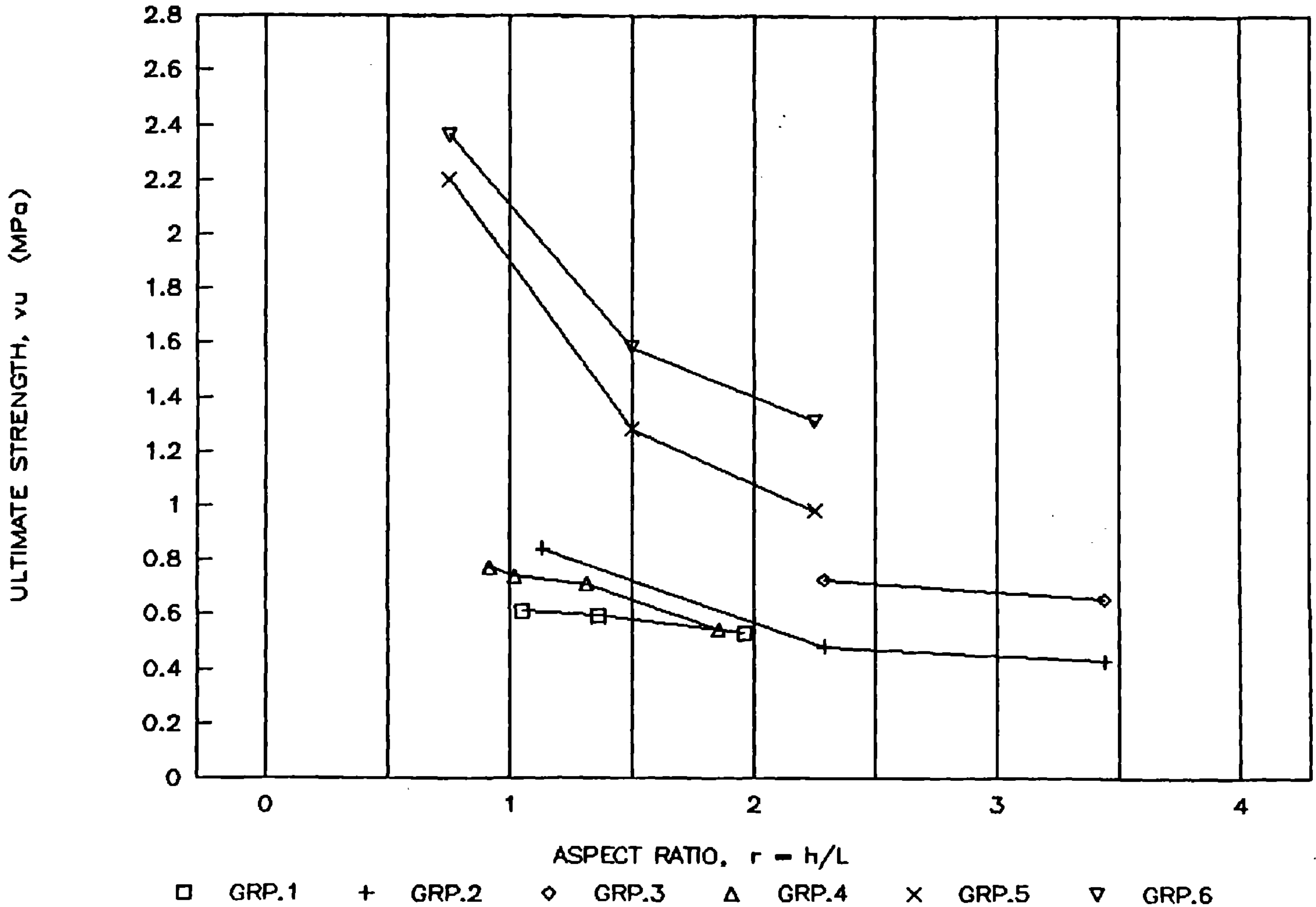

Figure 8. Effect of r on vc

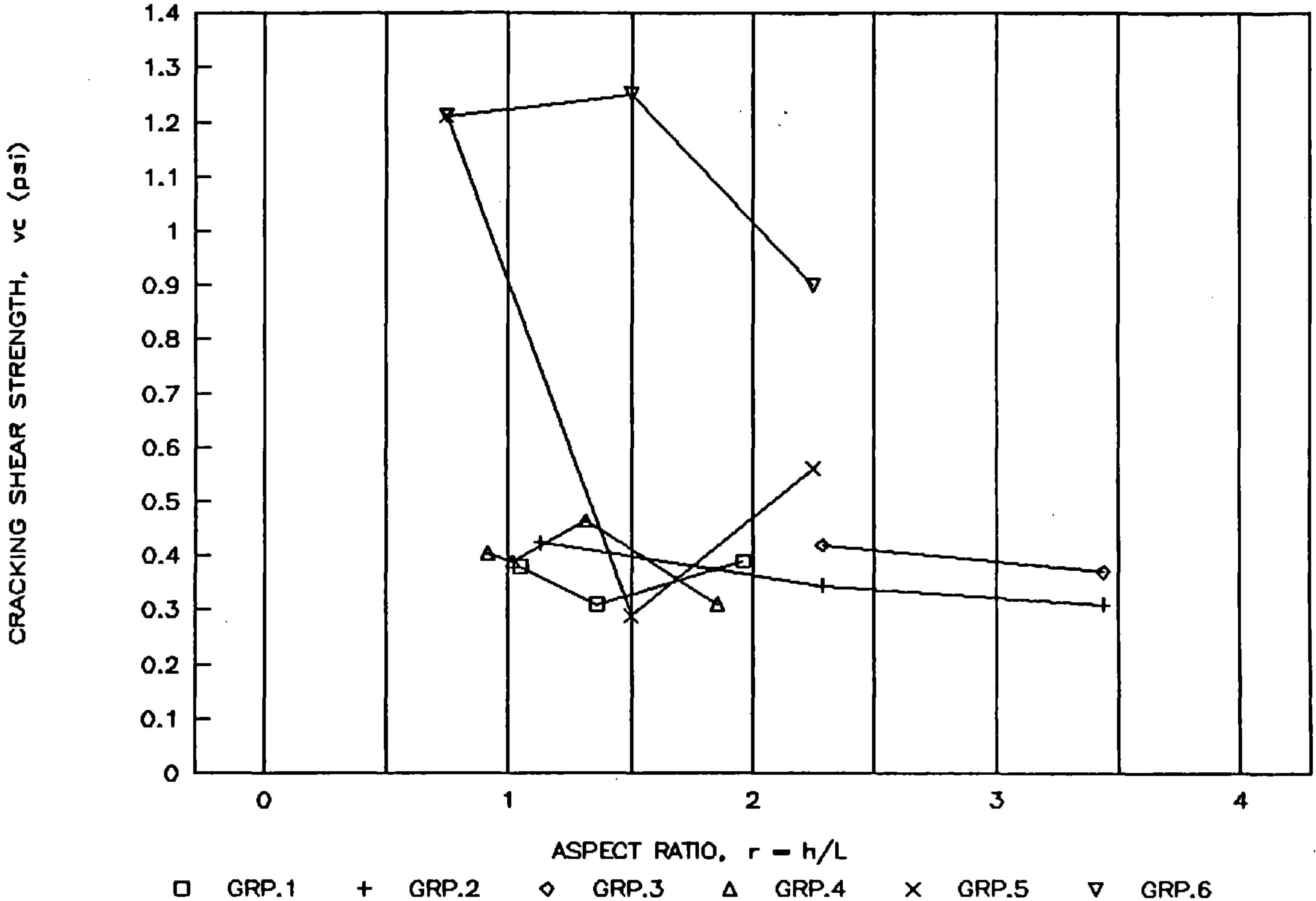

Figure 9. Effect of r on du and dc

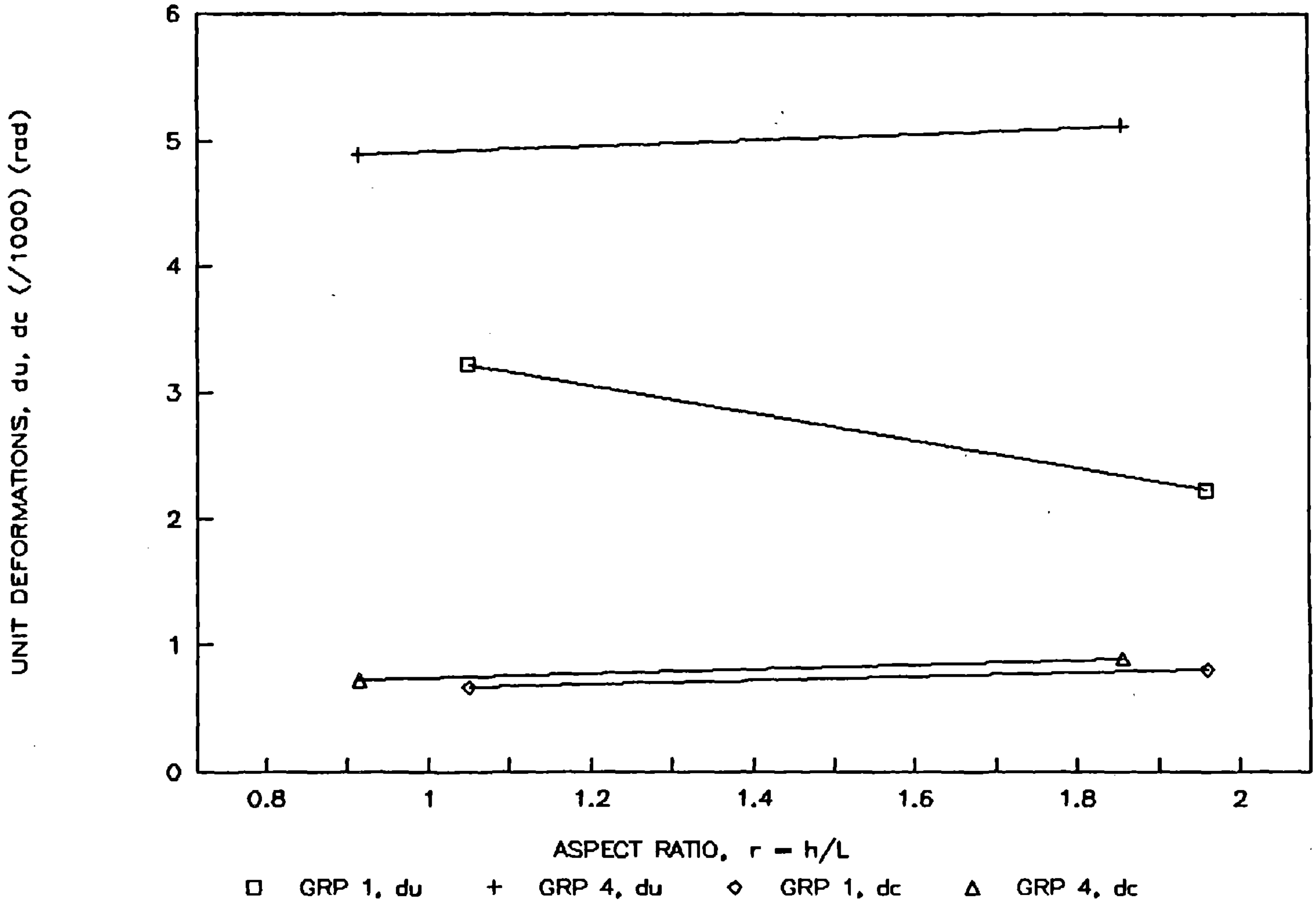

Figure 10. Effect of r on vu

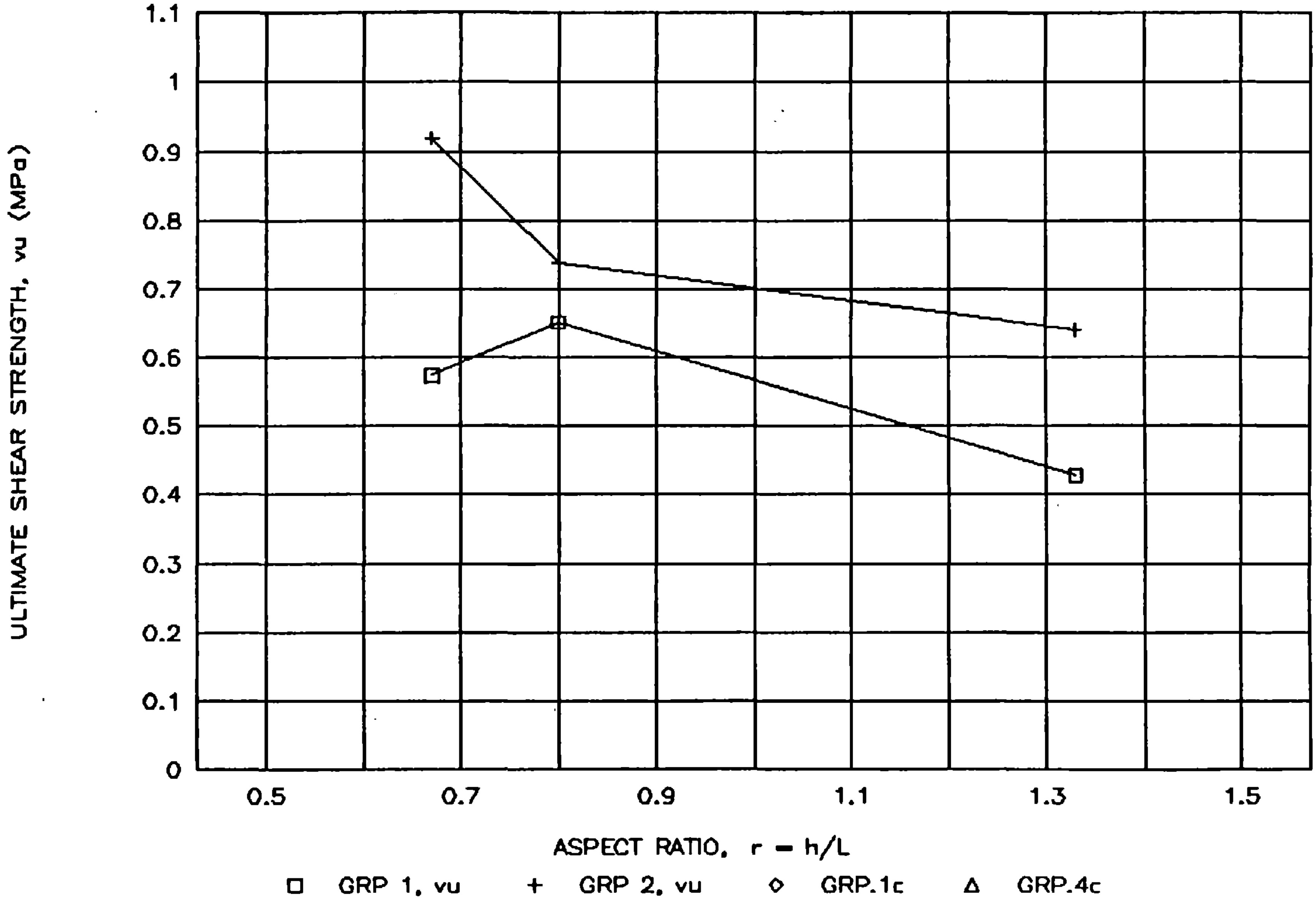

Figure 11. Effect of r on du

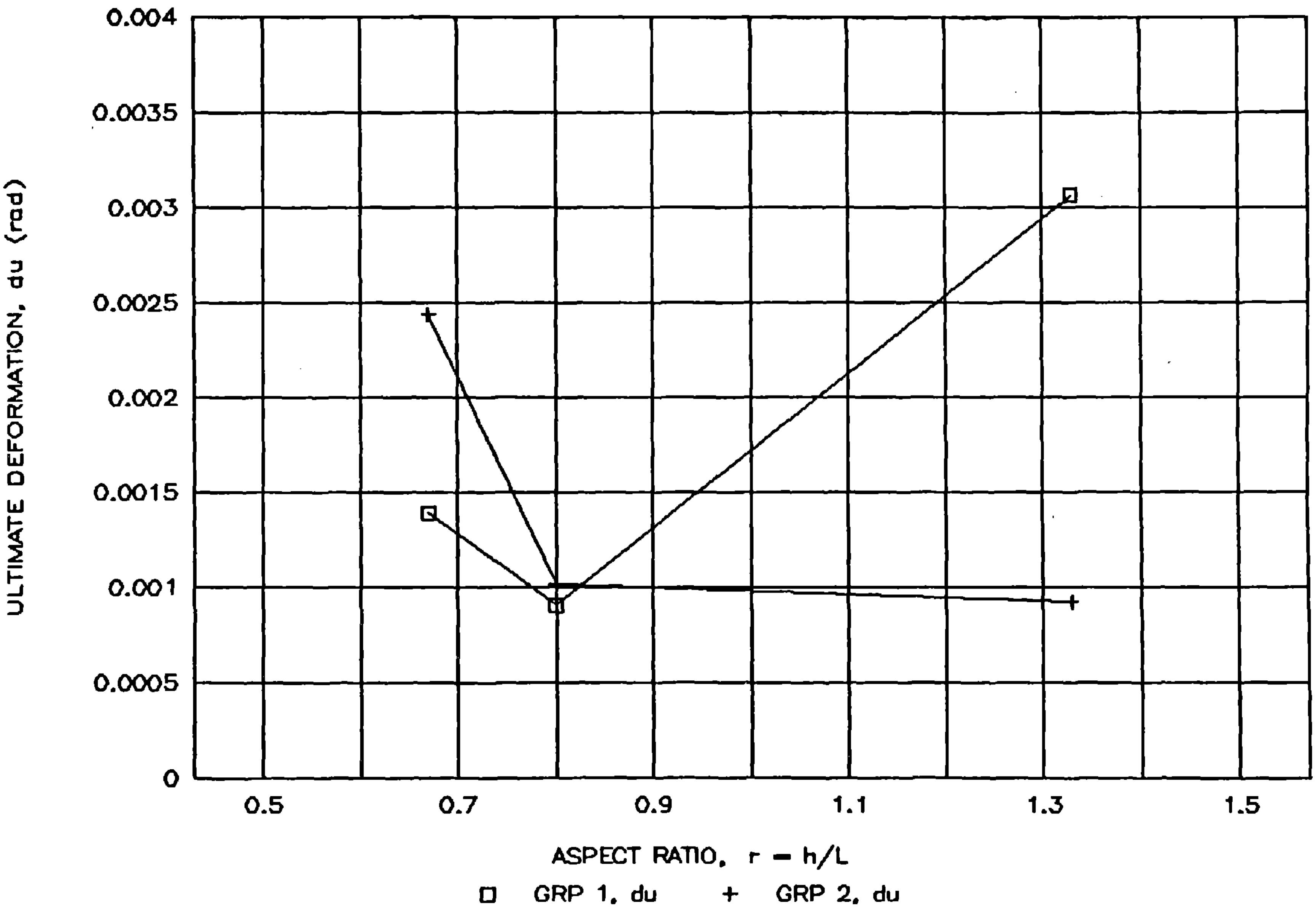

Figure 12. Effect of q on vu

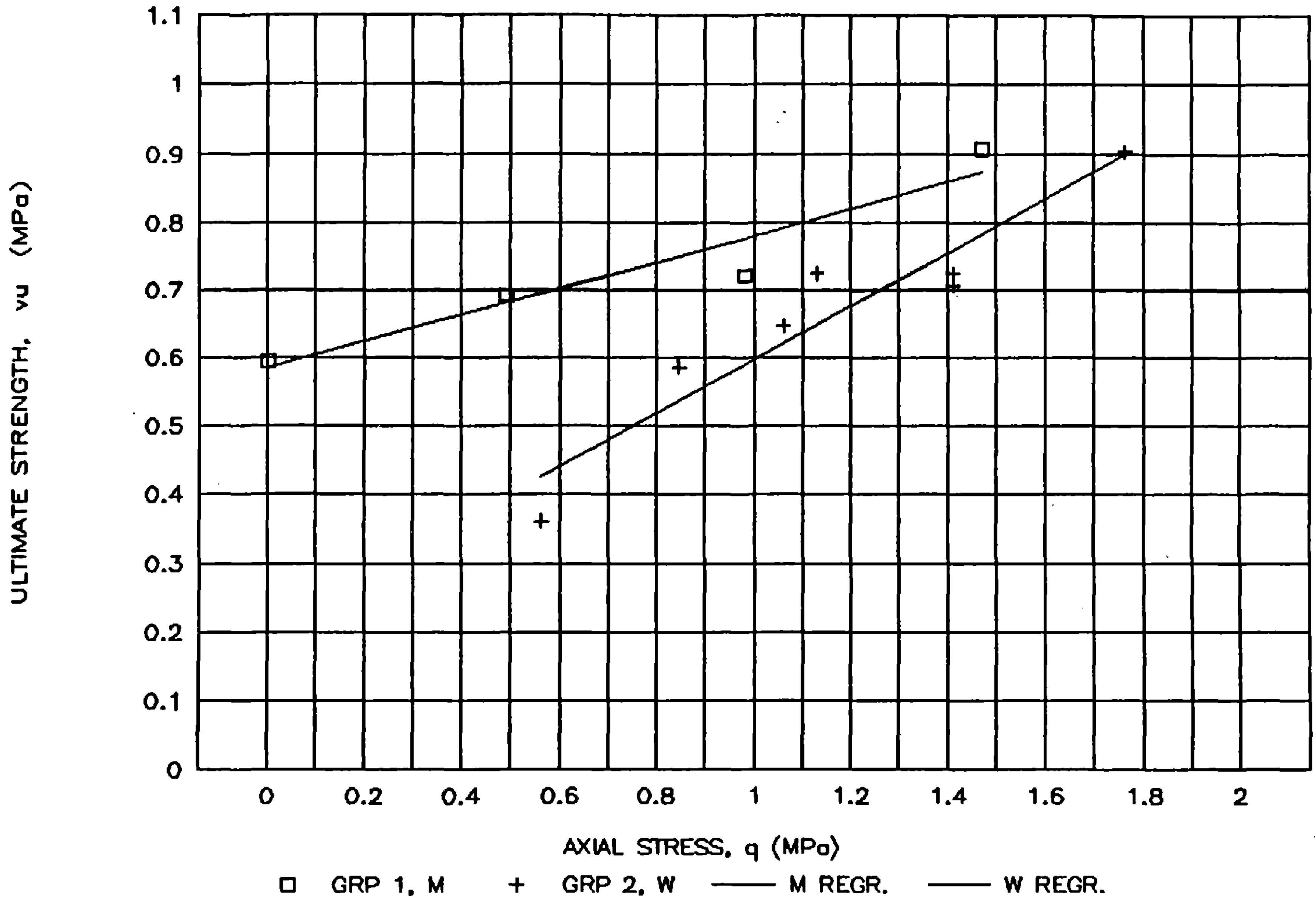

Figure 13. Effect of q on du

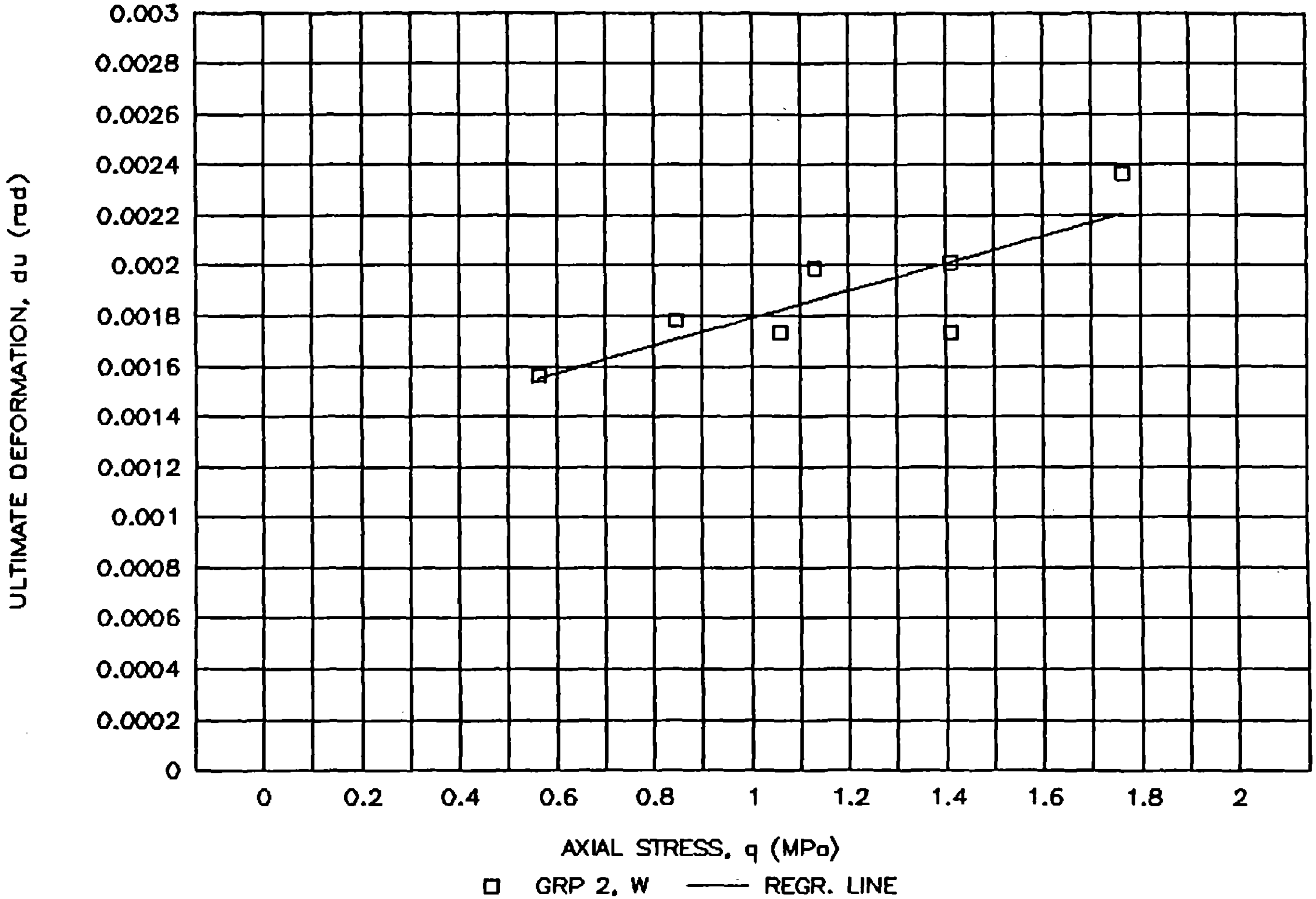

Figure 14. Effect of f'm on vu and vc

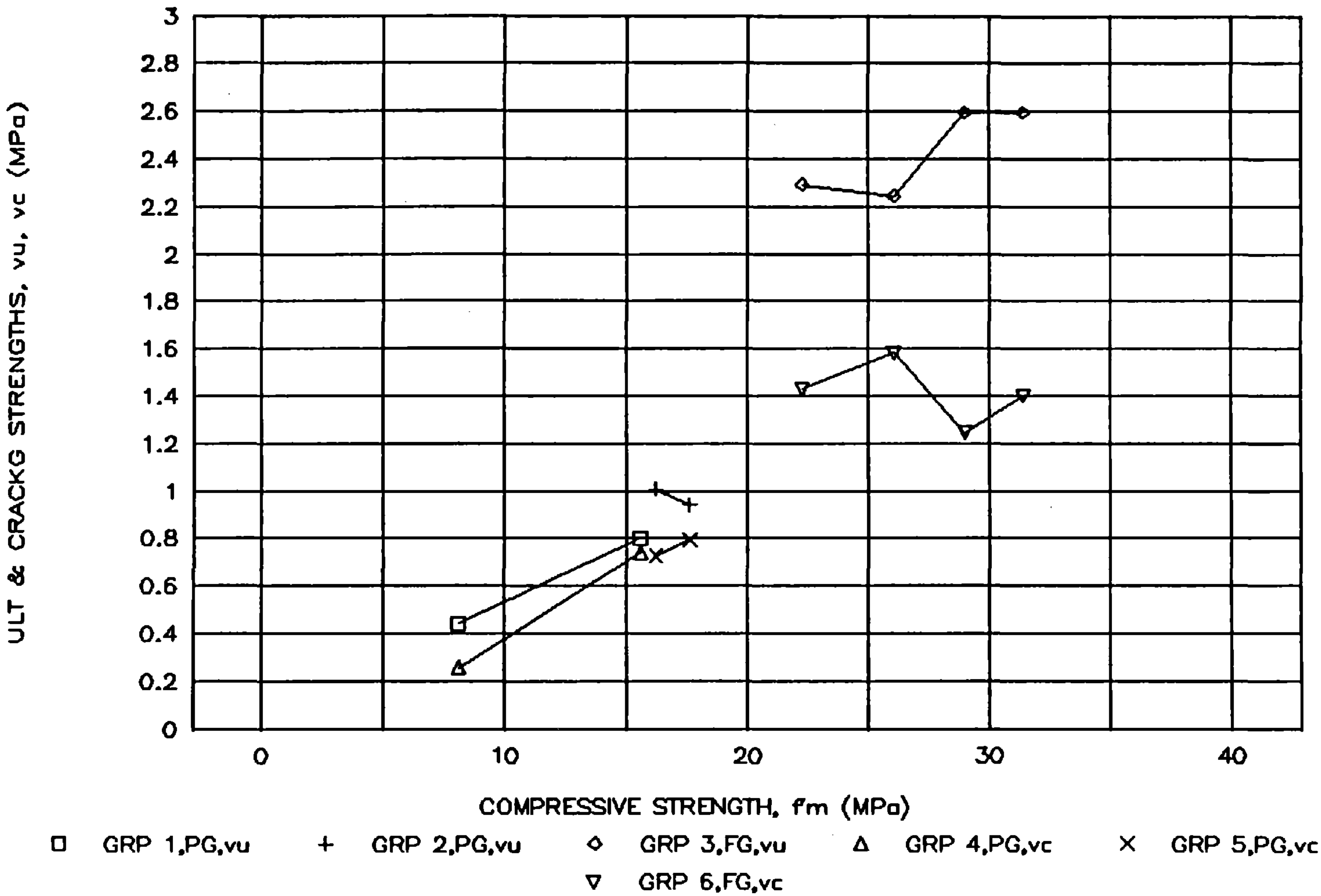

Fig. 15. Predicted effect of pv on vu

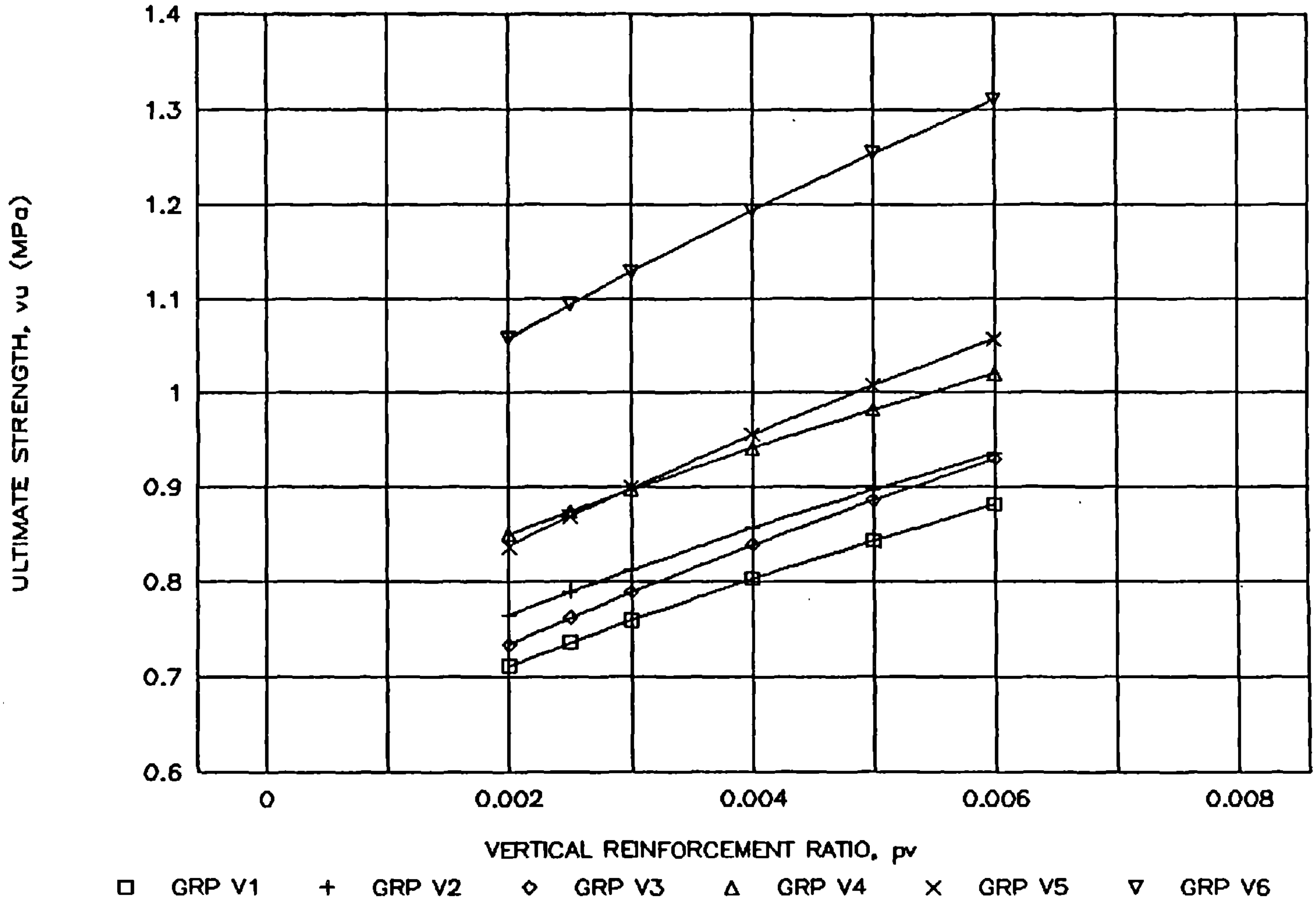

Figure 16. Predicted effect of ph on vu

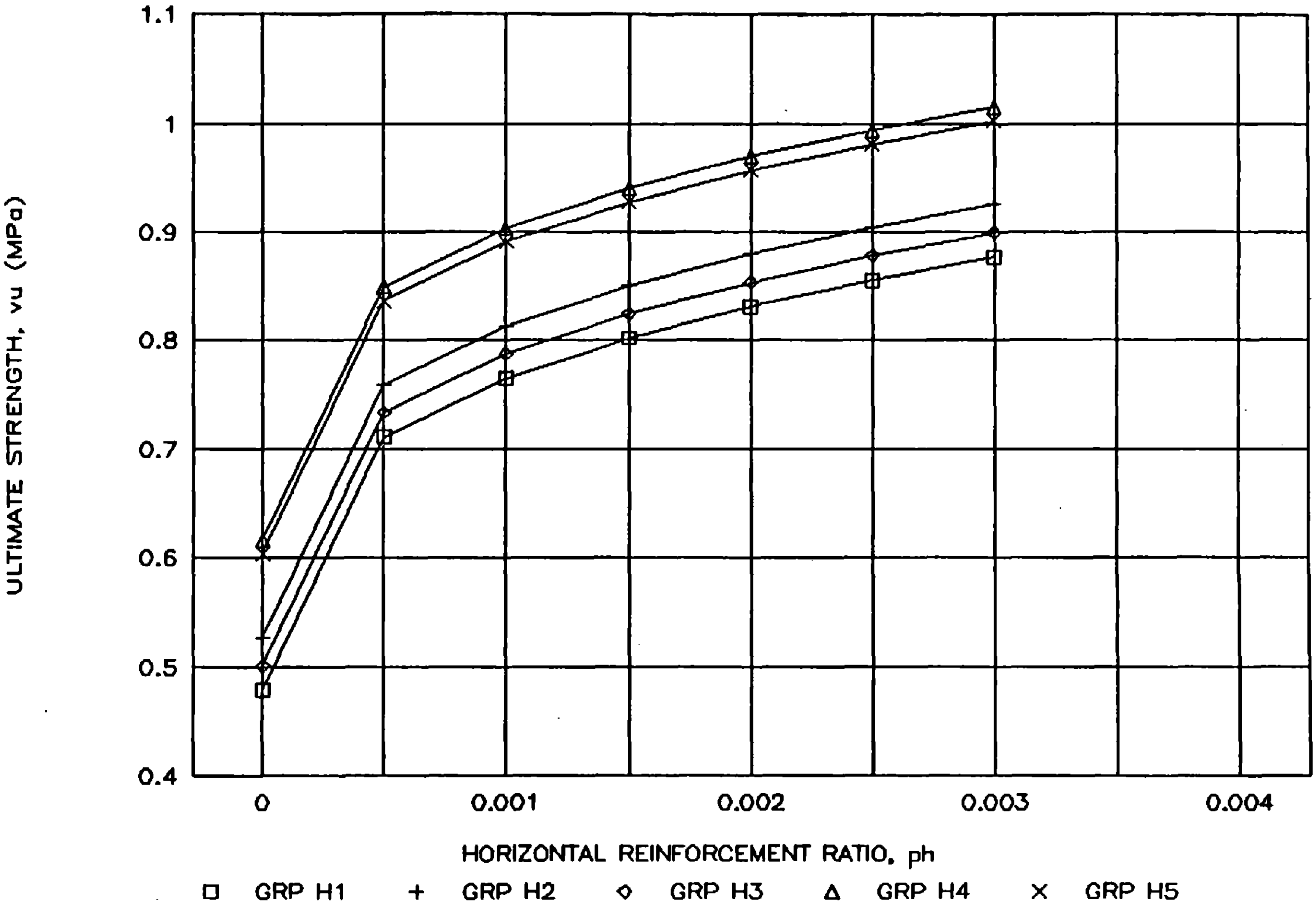

Figure 17. Predicted effect of r on vu