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DEPENDENCE OF COMPRESSIVE STRENGTH OF GREEN COMPACTS ON PRESSURE, DENSITY AND CONTACT AREA OF POWDER PARTICLES

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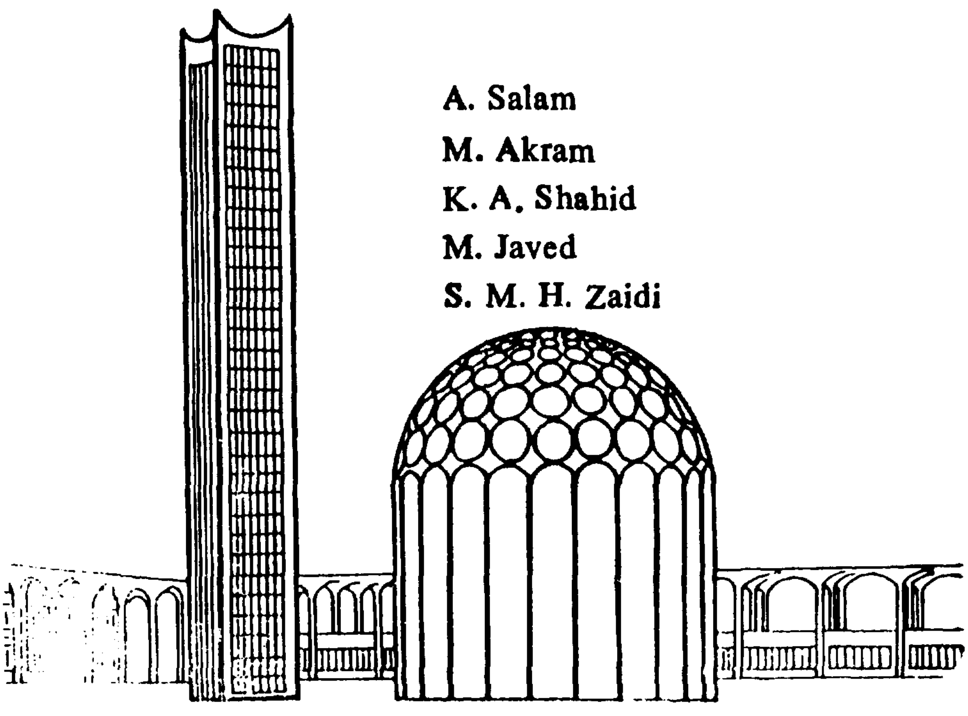

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ABSTRACT

The relationship between green compressive strength and compacting pressure as well as green density has been investigated for uniaxially pressed aluminium powder compacts in the range 0 - 520 MPa. Two linear relatioships occurred between compacting pressure and green compressive strength which corresponded to powder compaction stages II and III respectively, increase in strength being large during stage II and quite small in stage III with increasing pressure. On the basis of both, the experimental results and a previous model on cold compaction of powder particles, relationships between green compressive strength and green density and interparticle contact area of the compacts has been established.

Introduction

In order to produce structural parts using a typical powder metallurgy route, first requirement is to press the powders into compacts at room temperature. The green compacts thus obtained are not suitable for most applications until they are sintered. However, the green compacts should possess sufficient strength to allow necessary handling and manipulation before sintering.

Cold compaction process has generally been divided into three distinct stages. First stage is attributed to particle restacking and sliding without undergoing any deformation. Second stage is considered to consist of both elastic and plastic deformation during which interparticle necks are formed, area of particle contacts increases leading to welding of the prticles. As a result strength of the compact increases. Third stage of powder compaction has generally been related to bulk compression.

Many previous studies have been carried out on compacting pressure - green density relatinship of powder compacts but few have concentrated upon compacting pressure, green strength and green density relationships. Stromgren et al.[1] measured tensile strength of spherical cold isostatically pressed aluminium powder pressed to various densities and related it to interparticle contact area i.e. $\sigma \; \alpha \; (a/R)^3$, where a is the radius of the contact boundary and Ro is the mean radius of deformed powder particle pairs. This relationship was derived on the basis of non plastically deformed powder but authors considered the expression applicable to plastically deformed powders as well. James[2] suggested similar dependence of green strength on interparticle contact involvement in case of zinc powder but only during initial compaction stage whereas it was considered to be more dependent on interparticle bonding *forces of* attraction at higher pressures. Both Stromgren et al.[1] and James[2] reported a non linear increase in tensile strength with increasing compacting pressure, with inversions in strength occurring over intermediate pressure ranges. In a more recent work, Moon and Kim[3] have shown the green tensile strength of bidirectionally pressed copper powder compacts to be directly proportional to $(a/Ro)^2$, but not $(a/Ro)^3$. Green strength was also shown to be directly proportional to compacting pressure over specific pressure ranges.

It may be noted that pervious work described above employs tensile strenth data obtained from direct or indrect tests. Owing to difficulties in the direct tensile test due to the fragility and brittleness of the powder compacts and to avoid possible uncertainity in the results the work reported here makes use of compressive strength data rather than tensile strength in order to study green strenth, green density and compacting pressure. Also, it *is* typical *to* measure compressive strength for brittle solids e.g. ceramics rather than tensile strength because in such materials the largest flaw propagates unstably in tension whereas many flaws propagate stably to give general crushing in a compression test [4]. A number of tests are adopted for determining compressive strength of solids which have been recently reviewed by Darvell[5]. A test used for cylinderical specimens has been selected for use in present work.

Material and Experimental Techniques

An aluminium powder having average particle size of 29.7 microns was used in present work. Its particle size distribution is shown in Table 1. An SK Laser Micron Sizer PRO-7000 was used for particle size and particle size distribution determination. Bulk density and tap density of the powder were determined to be 0.8505 and 1.425 g/cm^3 respectively. Microscopic examination of the powder showed that the particles are of irregular shape.

Cold compaction was carried out in a single acting uniaxial press in the range 0 - 500 MPa using conventional die to produce cylinderical specimens. No die lubricant was used. Green densities were determined by physical measurements and an Instron Universal Testing machine was used to find green compresive strength of compacts. Strength of the compacts just before failure was taken as compressive strength.

TABLE 1

	Particle Size (microns)	% Volume
1	0.1	11.1
2	0.2	12.0
3	0.4	13.0
4	0.6	13.7
5	0.8	14.1
6	1.0	14.5
7	1.5	14.5
8	2.0	14.5
9	3.0	15.8
10	4.0	16.2
11	6.0	17.6
12	8.0	20.6
13	12.0	28.5
14	16.0	36.6
15	24.0	44.0
16	32.0	52.4
17	48.0	64.5
18	64.0	74.3
19	96.0	93.2
20	128.0	99.1
21	192.0	100.0

Results and Discussion

Figure 1 shows the dependence of green density of the powder compacts on compacting pressure. An increase in green density with icreasing compacting pressure may be seen, increase being large upto ~ 250 MPa and quite small at pressure higher than 250 MPa. Using Knopicky-Shapiro [6, 7] equation , data were also plotted as ln (1/1-Dr) vs. Compacting pressure as shown in Figure 2. Two linear relationships occurred, first form 85 to 250 MPa and second from 250 to 500 MPa. On the basis of a review of previous work on powder compaction presented by Hewitt et al [8], the first pressure range in which increase in ln (1/1-Dr) with pressure is linear may be taken as representative of region II which leaves the other pressure range as region III where slope of the curve decreases rapidly. Two slope factors corresponding to above two regions are 6.6×10^{-3} and 1.36×10^{-3} respectively. Figure 3 & 4 show the relationship between compacting pressure and green compressive strength on linear and ln - ln axes. Again two distinct linear relationships are seen, both corresponding to two regions of powder compaction identified earlier in Figure 2. In the pressure range which corresponds to region II a high increase in green compressive strength results on increasing the pressure whereas, in region III such increase in compressive strength is much smaller. Two similar linear relationships between pressure and green density were also reported by Moon and Choi [9] for bidirectionally pressed spherical copper powder compacts. This break in linearity was relatd to the effects of strain hardening which would slow down the increase in interparticle contact areas and metal particle would exhibit higher yiled strength for further deformation. The occurrence of two linear relationships between compacting pressure and green compressive strength in present work may also be related to strain hardening effects as suggested by Moon and Choi [9]. The same authors also reported a drop in green strength with increasing pressure at one point of the curve for isostatically pressed copper powder compacts. Similar observations were also made by Stromgren et al [1] and James [2] for isotatically pressed aluminium and die pressed zinc powders respectively. However, no such drop in strength was observed in present work.

A nearly indentical point of change of slopes on the two graphs shown in Figures 2 & 3 indicate that the green compressive strength is related to interparticle contact area as well as green density of the powder compacts. In order to find interparticle contact areas of the compacts following geometrical relationship proposed by Moon and Kim [3] was used:

$$a/Ro = Dr^{-1/3}[0.806 - 1.03(1-Dr)^{1/3}] \qquad \text{(i)}$$

Where a is the radius of the contact area, Ro the original spherical powder particle radius and Dr the relative theoretical density of the powder compact after pressing. This relationship which was derived for simple cubic packing of spherical powder particles may be applied to present situation i.e. for packing of irregular shaped powder particles if it is assumed that the initial area of contact formed on any two particles pressed together is circular in shape and that it would gradually lose its shape on increasing in size. In addition to this, in the above model the ratio a/Ro is a function of relative density only,and the packing factor of the powder used in present work is the same as simple cubic packing . Therefore the model of Moon and Kim [3] may be considered true for packing of irregular shaped powder particles leading to a low density compact and only approximately true for packing of particles leading to a high desnity compact. Variation of green strength with $(a/Ro)^2$ is shown in Figure 5. It may be seen that the green compressive strength is approximately proportional to $(a/Ro)^2$ because scatter in the data increases at higher values of $(a/Ro)^2$. Scatter in the data increases even more when green strength values are plotted against $(a/Ro)^3$ .This is not different from the observations of Moon and Kim[3] according to which green strength of compacts of a spherical copper powder was found proportional to $(a/Ro)^2$. Green strength vs. $(a/Ro)^2$ data were also plotted on logrithmic scale as shown in Figure 6. It may be seen that the scatter in the data has reduced. Therefore it is considered here that it would be more appropriate to relate green strength to particle contact area via an equation of the following type:

$$\sigma = K1[(a/Ro)^2]^{m_1} \qquad \text{(ii)}$$

where K1 and m_1 are constants. In present case values of m_1 and K1 were found to be 0.74 and 287 respectively (Figure 6).

Values of σ obtained from equation (ii) were plotted against $(a/R0)^2$ shown as continuous line in Figure 7. It may be seen that the theoretical curve is not far off from the experimental data points.

In order to find a relationship between green density and green strength of the compacts, data were initially plotted on linear scale but it was difficult to identify any satisfactory direct relationship between the two. However, when the data were plotted on logrithmic axes, a linear relationship was observed suggesting that the green compressive strength may also be related to green density via an equation of the type given in (ii). Values of constants K and m were found to be 0.41 and 5.62 respectively. Therefore green strength variation with density may well be represented by following equation:

$$\sigma = K2\ \rho^{m} \qquad \text{(iii)}$$

From Figure 8, it may be seen that the theoretical curve is in close agreement with experimental data points. Equation (iii) is similar to the following modelproposed by German(10) for sintered materials:

$$\sigma = k1\sigma_0\rho^{m} \qquad \text{(iv)}$$

where k1 and m are constants for a given situation and σ_0 is wrought strength.

An alternate way to find a relationship between green density and green compressive strength of the compacts could be possible by using equation(i).

Rewritting (i) after replacing Dr by ρ/ρ_t:

$$a/Ro = \rho^{-1/3}[0.806\ \rho_t^{1/3}-1.031(\rho_t-\rho)^{1/3}] \qquad (v)$$

Substituting value of a/Ro in equation (ii) and rewriting

$$\sigma = 287[\{\rho^{-1/3}(0.806\rho_t^{1/3}-1.031(\rho_t-\rho)^{1/3})\}^2]^{0.74} \qquad (vi)$$

Simplifying

$$\sigma = 287[0.806\rho^{-1/3}\rho_t^{1/3} - 1.031\rho^{-1/3}(\rho_t-\rho)^{1/3}]^{1.48} \qquad (vii)$$

which is a relationship between green strength and green density. Using this relationship values of σ were calculated and plotted against ρ as shown in Figure 9. It may be seen that the theoretical curve is again in reasonable agreement with the experimental data points which nevertheless suggests that in addition to equation (iii), green strength may also be related to green density via equation (vii).

Conclusions

Following conclusions may be drawn from the present work on aluminium powder:

1- Two distinct linear relationships occurred between compacting pressure and green compressive strength which corresponded to regions II and III on pressure- ln(1/1-Dr) powder compaction data.

2- A high increase in green strength was observed with increasing pressure in region II as compared to little increase in strength with pressure in region III.

3- Highest value of green compressive strength i.e. 71 MPa was obtained at the highest compacting pressure used.

4- Green compressive strength may be related to particle contact area of the compacts via an equation of the following form:

$$\sigma = k1[(a/Ro)^2]^{m1}$$

where k1 and m1 are constants.

5- Variation of green compressive strength with density of the compacts may be expressed with either of the following relationships:

$$\sigma = k2\ \rho^{m2}$$

$$\sigma = 287[0.806\ \rho^{-1/3}\rho_t^{1/3} - 1.031\ \rho^{-1/3}(\rho_t-\rho)^{1/3}]^{1.48}$$

where σ, ρ and ρ_t are green strength, green density and theoretical density respectively, and k2 and m2 are constants.

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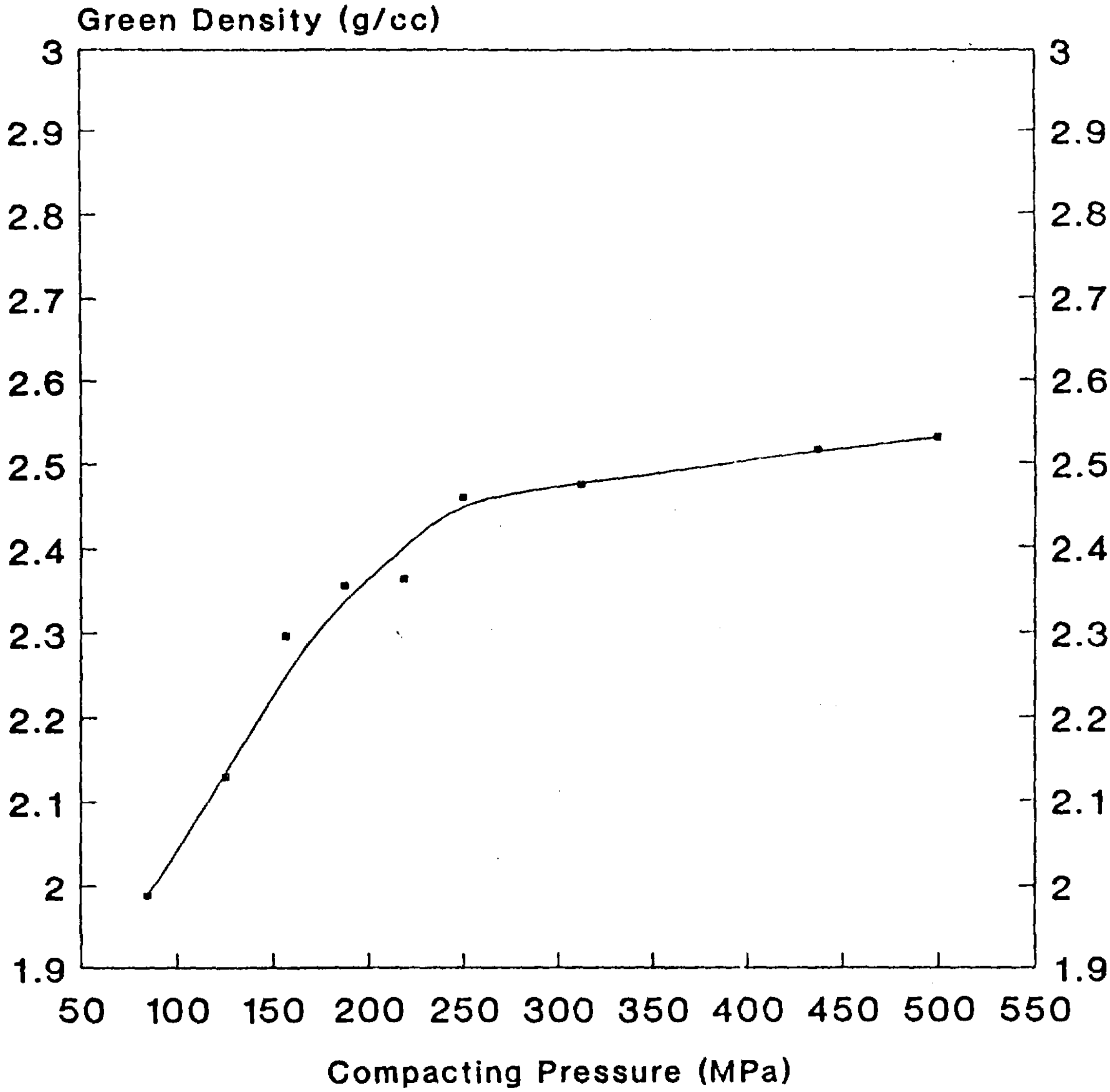

• Uniaxial pressing

Figure 1: Relationship between compacting pressure and green density

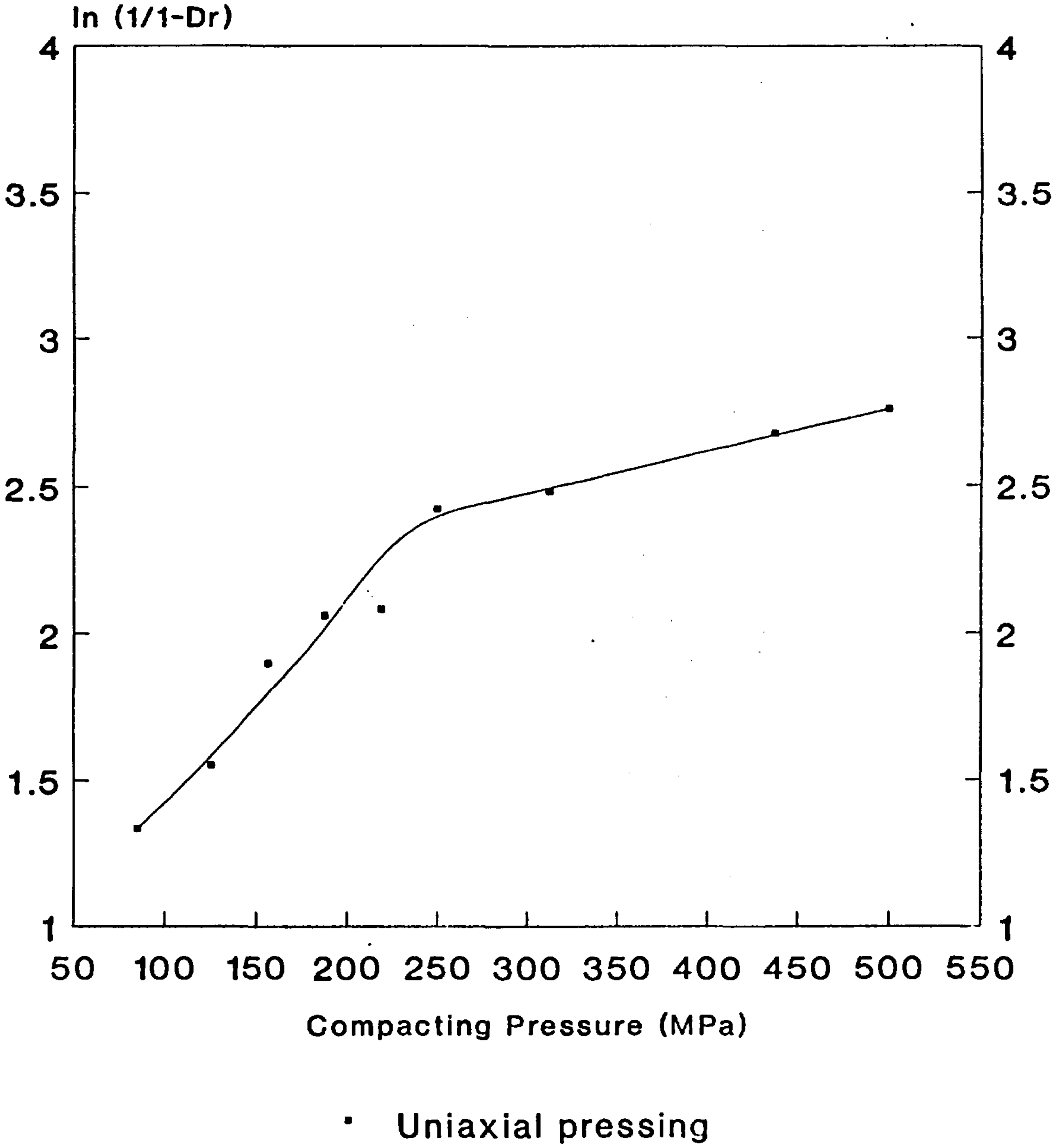

Figure 2: Relationship between compacting pressure and ln (1/1-Dr)

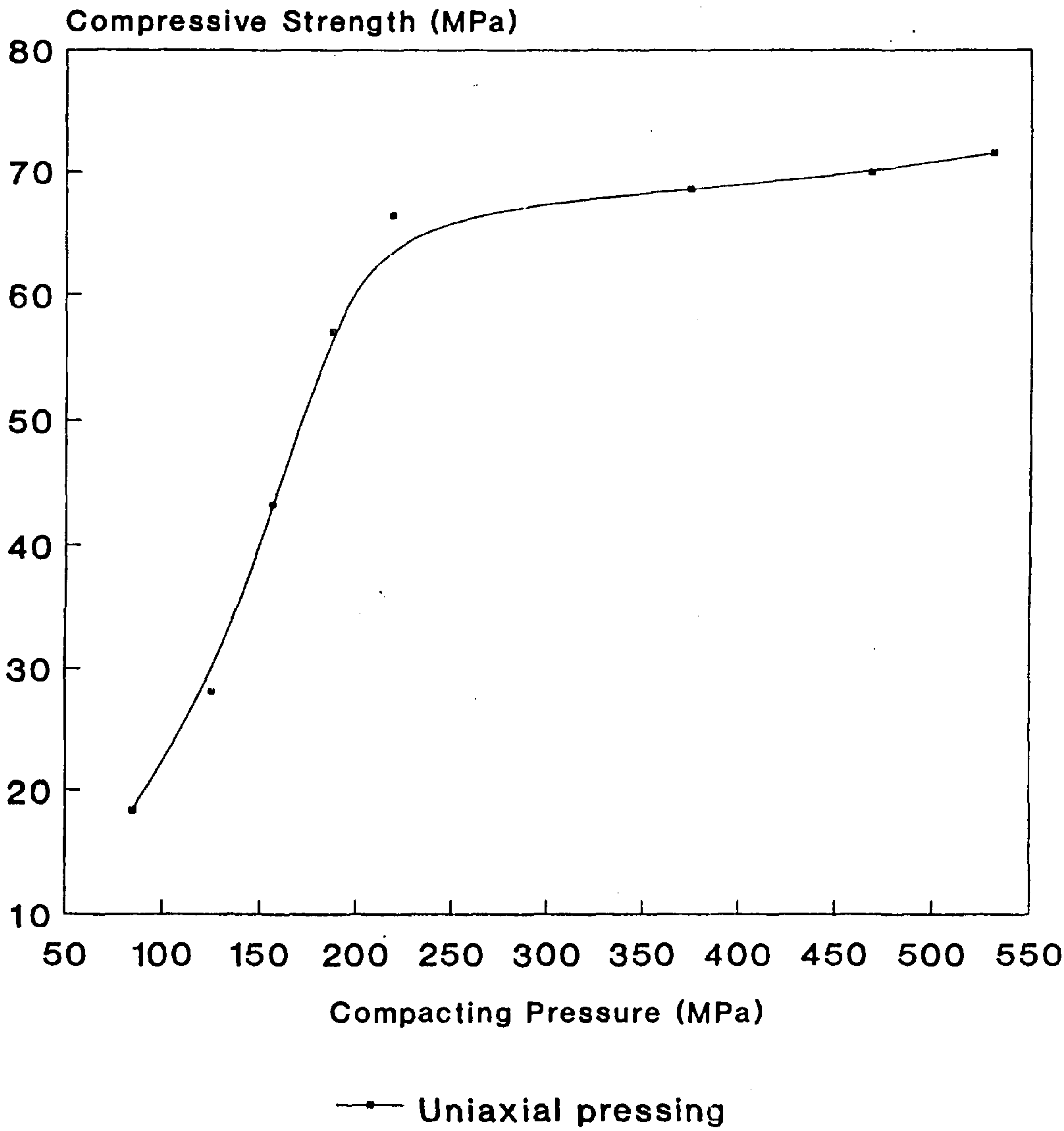

Figure 3: Relationship between compacting pressure and green compressive strength

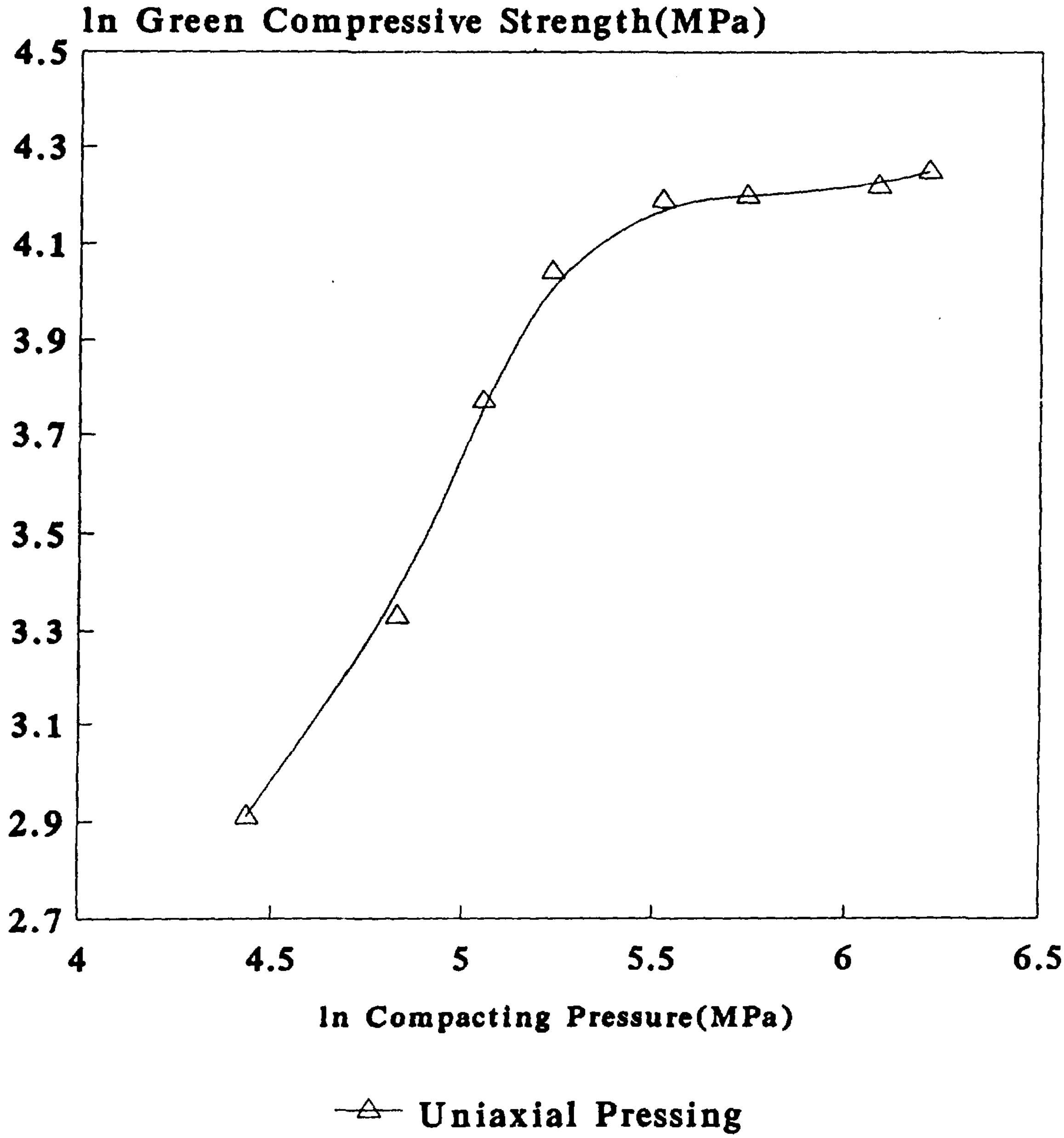

Figure 4: Relationship between compacting pressure and green compressive strength

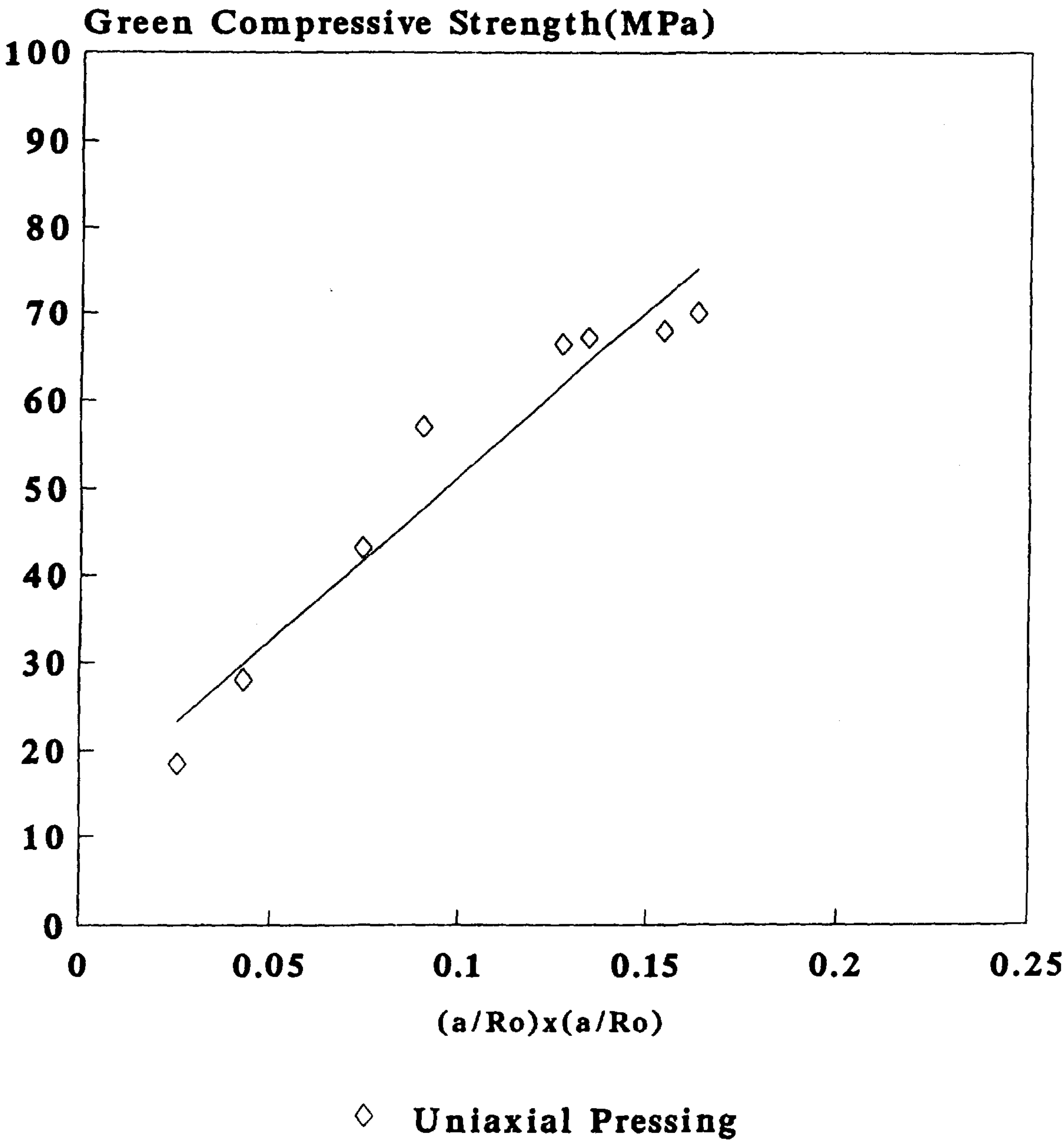

Figure 5: Relationship between (a/Ro)x(a/Ro) and green compressive strength

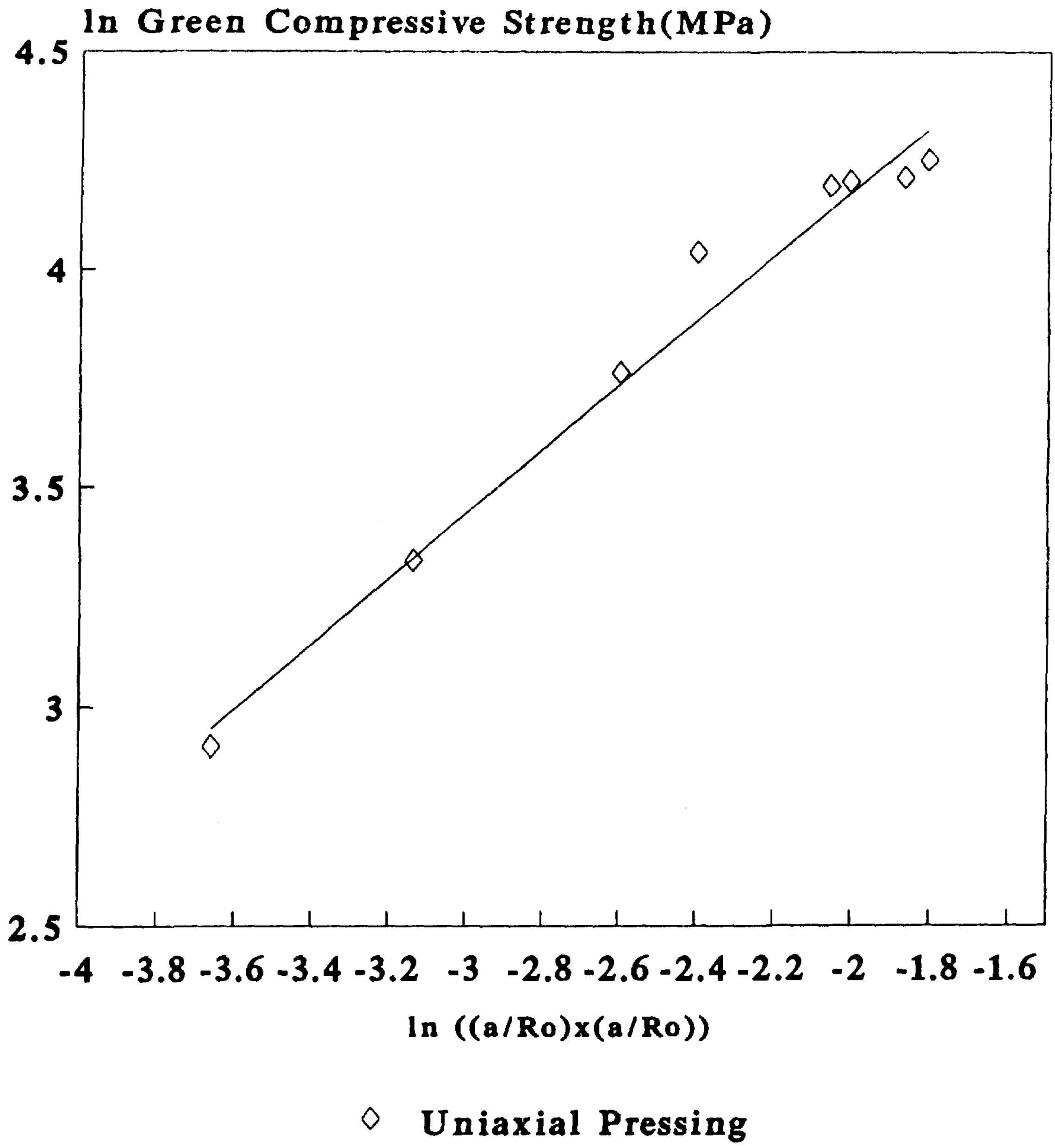

Figure 6: Relationship between (a/Ro)x(a/Ro) and green compressive strength

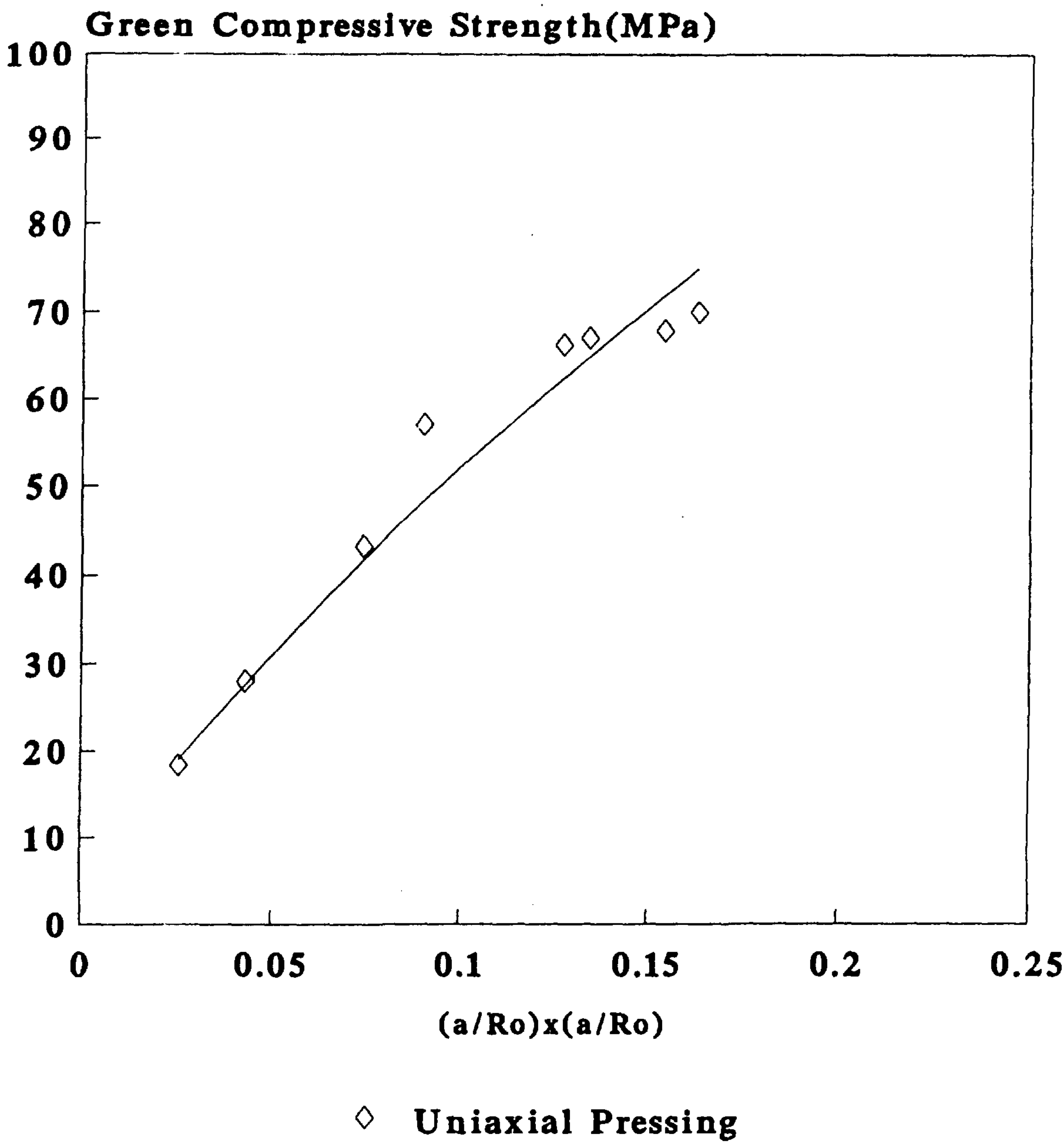

Figure 7: Relationship between (a/Ro)x(a/Ro) and green compressive strength

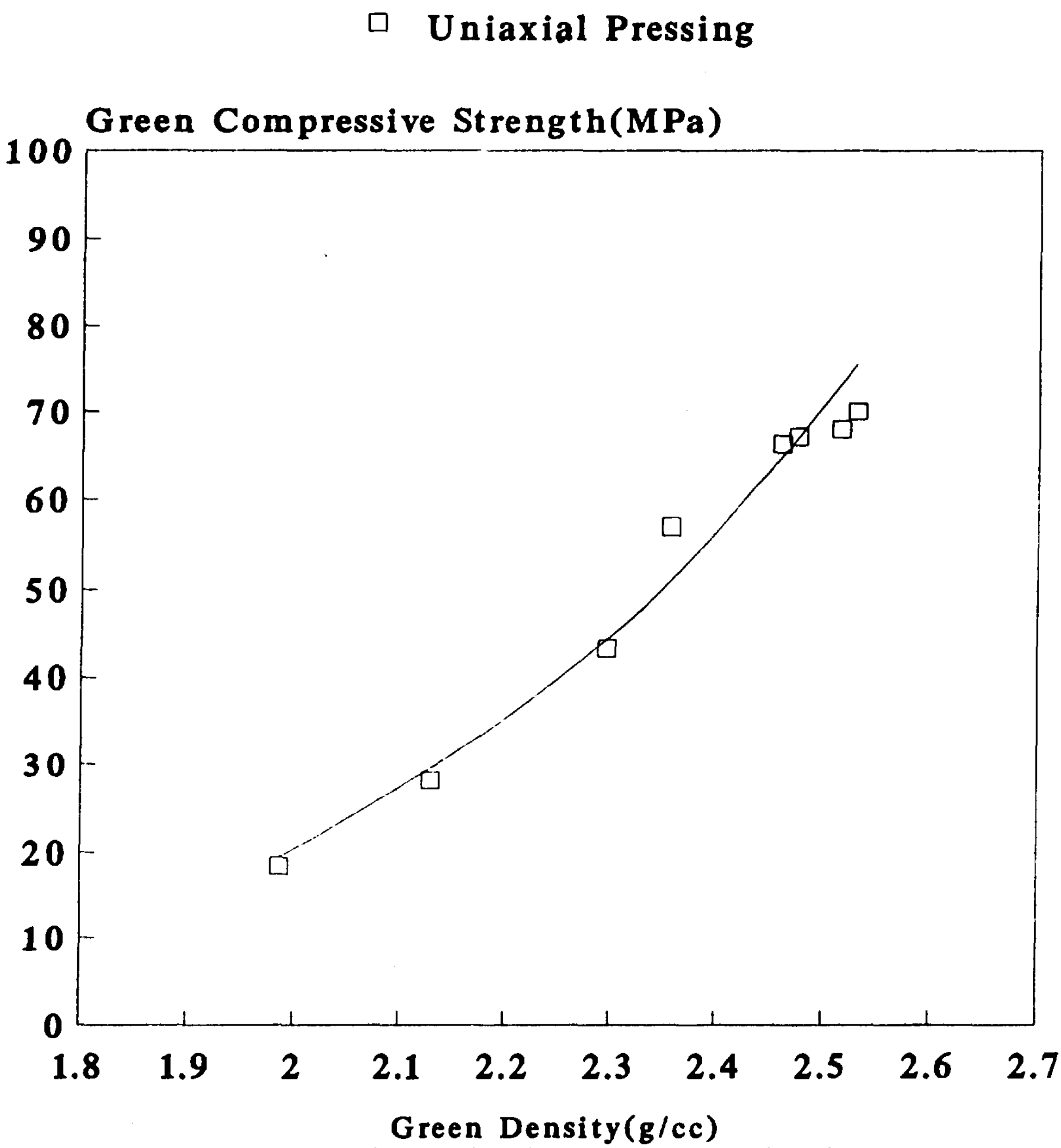

Figure 8: Relationship between green density and green compressive strength

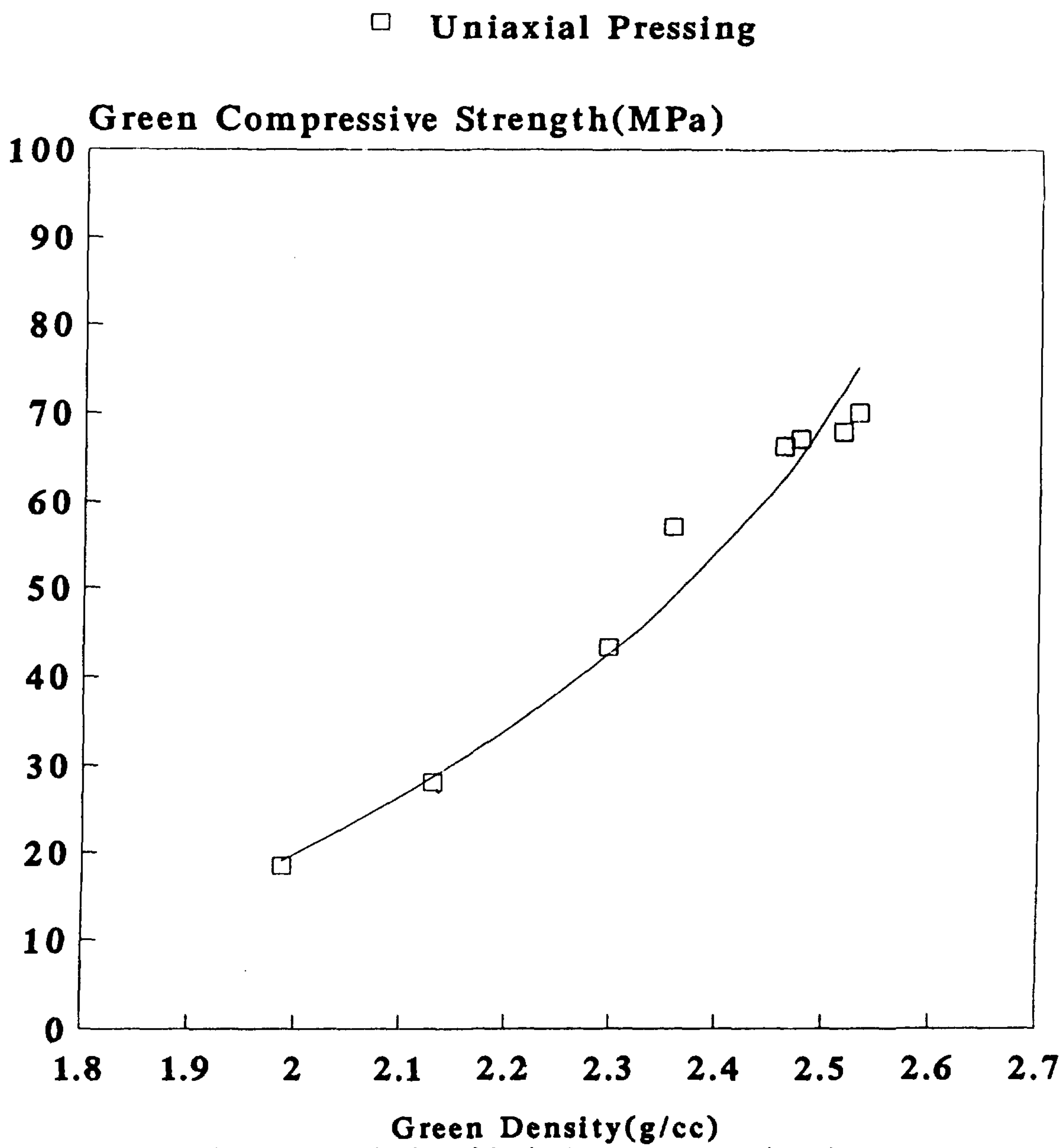

Figure 9: Relationship between green density and green compressive strength