JOURNAL OF MATERIALS SCIENCE 22 (1987) 3321–3327

Mechanical properties of implosively compacted suspension homopolymer S 57/116 PVC powder

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The response of an aggregate of commercially produced particulate polymeric material to static and shock consolidation is described. The presence of interparticle bonding, associated with the explosive process, considerably increases the strength and hardness of the compact, as compared with static processing, and enables a high degree of densification to be attained. The final properties of the compact are influenced by the initial particle size, tap density, and the characteristics of the container. For an aggregate varying in particle size from −150 to 212 μm, optimal conditions are reached at shock pressures of between 10 and 11 GPa.

1. Introduction

Although the technique of shock (usually explosive) consolidation of metallic and ceramic powders is well established [1, 2], its application to compaction of polymeric materials is only now entering its preliminary stage.

The effect of the passage of a suitably profiled shock wave through an aggregate of a particulate material is to produce a compact of high degree of densification and strength; the latter resulting from the intergranular or interparticle bonding. Additionally, and depending on the substance used, chemical and physical changes may occur such as synthesis of a new material, change of phase, enhancement of the degree of reactivity, change in the electric and magnetic properties and a general increase in the incidence and level of microfaults [3–5].

From the point of view of a polymeric material, the considerable attraction of explosive consolidation lies in the relatively low level of adiabatic heat generated, and in a high rate of heat dissipation. Consequently, thermoplastics, in particular, are likely to be shaped in this operation without necessarily suffering degradation of their properties which is often associated with conventional processing.

The manufacture, further manipulation and use of such compacts require the knowledge of the mechanical properties and the response of not only the final product, but also of the starting aggregate. This is of particular importance if the polymeric material is to be used as a matrix for a mixture of either metallic or ceramic powders [6–8]. The effect of the initial grain/particle size, tap, density, the material and geometry of the container and of the level of impact energy supplied (and, hence, pressure generated) will be reflected in the degree of densification and bonding. The interrelation between these various parameters and the material properties of the final compact is the subject of the present paper.

Unlike, however, an examination of a number of polymeric and non-polymeric mixtures, reported earlier [6–8], this experimental investigation is concerned with a single homopolymer PVC powder which, from the industrial viewpoint, is both representative of the group and also has practical applications.

The object of the investigation is to establish a wide range of practical material data that would provide an insight into the likely behaviour and properties of other particulate, polymeric substances.

Because in the case of PVC, and similar materials, conventional, static processing is possible, a comparison between the two techniques is drawn and the advantages of using shock consolidation are indicated in terms of high levels of green density, hardness and compressive strength attainable.

The resemblence between patterns of response to shock treatment between polymers and ceramics (on a macro scale in particular) supports the view, expressed above, that it is legitimate to generalize, within reason, on the basis of the results of a single-polymer investigation [9–12]. This situation obtains, because the three bonding mechanisms, associated with explosive techniques of friction, fusion and pressure welding are common to all the particulate, shock-treated materials [1, 4, 5, 7, 8, 12].

2. Implosive compaction

2.1. Compacting system

Implosive compaction was effected by means of a direct system. In this, the powder to be compacted is contained in a metal cylinder which, in turn, is surrounded by a hollow, cylindrical charge of a powdered, high explosive. The charge is detonated at the apex of a cone forming the upper closure of the

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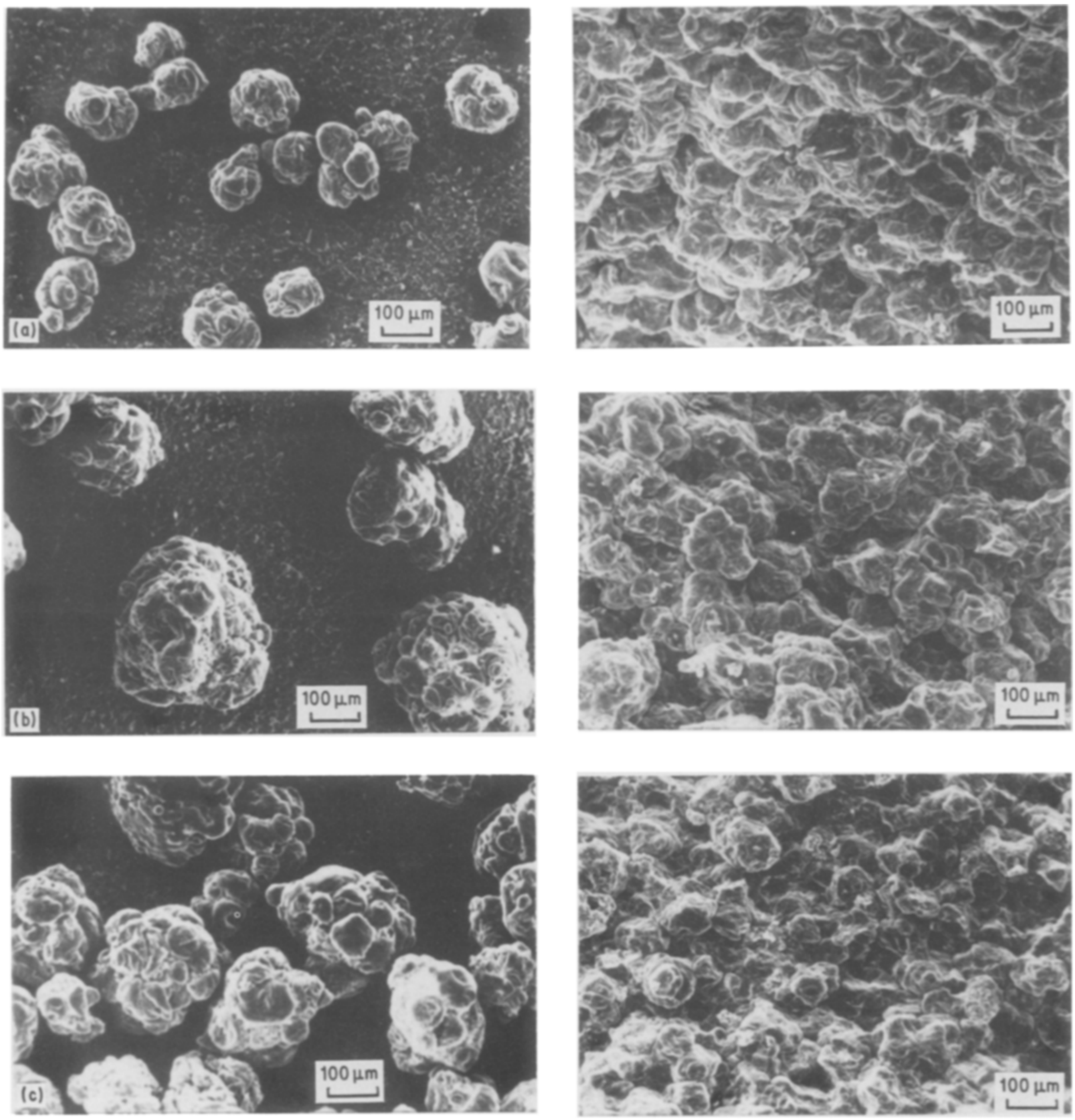

Figure 1 Morphology of the powder (left-hand side) and of explosive fracture surface compact (right-hand side) at a pressure of 10 GPa. (a) $< 150\,\mu$m, (b) $> 212\,\mu$m, (c) mixture.

container. In this way, a plane detonating front is generated and is then propagated downwards along the surface of the vertical container. Radial pressure and stress waves effect the compaction of the powder.

To compare the properties of compacts so obtained with those of statically consolidated samples, static compaction was also carried out, but in steel dies and on a 50T Denison press.

2.2 Materials

A Corvic-type ICI suspension PVC polymer S 57/116 was selected as being representative of the standard materials used conventionally. The average grain size of the mixture was $160\,\mu$m; the actual range lying within -150 and $+212\,\mu$m. The apparent density of the as-supplied material was $0.56\,\mathrm{g\,cm^{-3}}$, the average tap density $0.66\,\mathrm{g\,cm^{-3}}$, with the theoretical density being $1.4\,\mathrm{g\,cm^{-3}}$. The glass transition temperature of this material is 82° C and the decomposition temperature is 237° C.

In addition to using the as-supplied material, the powder was also separated into fractions containing particles less than $150\,\mu$m and more than $212\,\mu$m in size. The average tap density was increased to provide additional starting points. Post-compacting green density, compressive strength to fracture, hardness, and creep properties of the compact were assessed and related, generally, to the properties of the container. The material and geometry of the latter are of importance because the rigidity of the powder-containing system minimizes or nullifies the effect of the reflected, tensile pressure wave that can damage the already formed compact.

Steel, copper and aluminium cylinders ranging in wall-thickness from 2 to 4 mm were used as

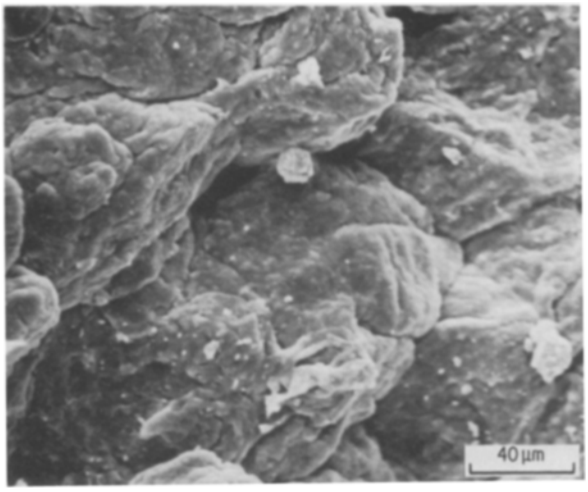

Figure 2 Morphology of the fracture surface of a static compact obtained at a pressure of 380 MPa.

containers. The compaction produced cylindrical polymer specimens 150 mm long and 24 mm diameter.

2.3. Implosive and static compaction

The implosive operations used ICI Trimonite 3 powdered explosive with the velocity of detonation varying between 2.5 and 3 km sec^{-1} (depending on the thickness of the charge layer). Pressures generated and available for powder consolidation ranged, accordingly, from 7 to 13 GPa. In static compaction, pressures of up to 500 MPa were required.

3. Consideration of results

3.1. Morphology

3.1.1. Explosively consolidated material

Fractionalization of the powder into three particle-size groups results in the existence of a +212 μm fraction of 40% by volume, another of 25% of −150 μm, and of the mixture of 35% of −212 and +150 μm particles. Fig. 1 shows the respective particle sizes and the consolidated (fracture surface) compacts obtained at a pressure of 10 GPa. The degree of consolidation is high in all three cases, but, nevertheless varies within this range with the particle size, although all fractions considered have undergone a considerable degree of plastic deformation accompanied by grain flattening. The degree of porosity and, consequently, green density is the highest for the large particle fraction (Fig. 1b) and the smallest for the mixture (Fig. 1c).

For a given level of available compacting energy, as is the case here, the initial grain or particle size will dictate the magnitude of local interparticle collision velocities because the stand-off distance, or the initial separation of the grains depends on this parameter. With large particle fraction, the energy supplied is insufficient to accelerate and deform plastically the elements of the aggregate and consequently a certain degree of porosity exists in the compact. At the other extreme of the small particle aggregate, the level of energy is sufficient to accelerate the particles, but the stand-off distances are too small to allow the build-up of high-impact velocities.

Porosity is reduced in comparison with the +212 μm fraction, but it is not entirely eliminated. It is, in fact, the mixture which, by providing a variety of collision possibilities as well as some comminution of larger particles, and the filling of voids with smaller, offers the best compacting and bonding conditions. As seen in Fig. 1c porosity is virtually absent and the closely packed and bonded structure appears to be well "homogenized".

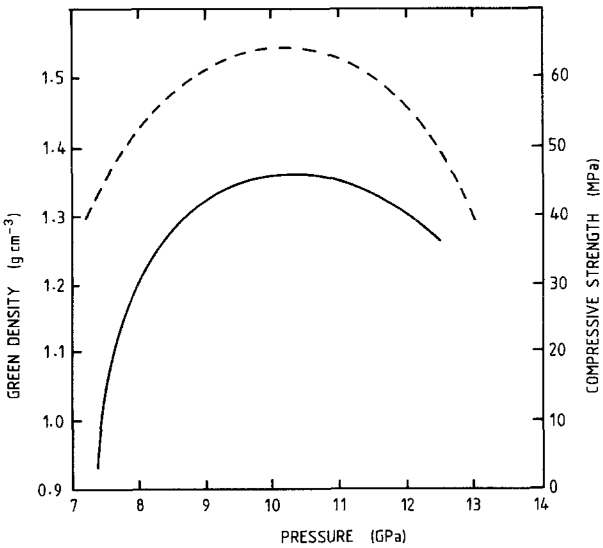

Figure 3 Variation of (——) green density and (– – –) compressive strength with compacting pressure for the as-supplied mixture. (Steel container, 2 mm wall thickness.)

3.1.2. Statically consolidated material

In contrast to the explosively compacted polymer, a static compact of the mixture, obtained at a relatively high static pressure of 380 MPa (Fig. 2), shows a very high degree of porosity and a very low degree of plastic deformation. The separation of the individual particles indicated the absence of bonding and the small sized grains do not fill-in the voids, but appear to be loosely dispersed throughout the structure.

3.2. Explosive–static compacts: a comparison

Figs 3 to 5 provide bases for a comparison between the properties of explosively and statically manufactured compacts. Plots in Figs 3 and 4 represent mean curves,

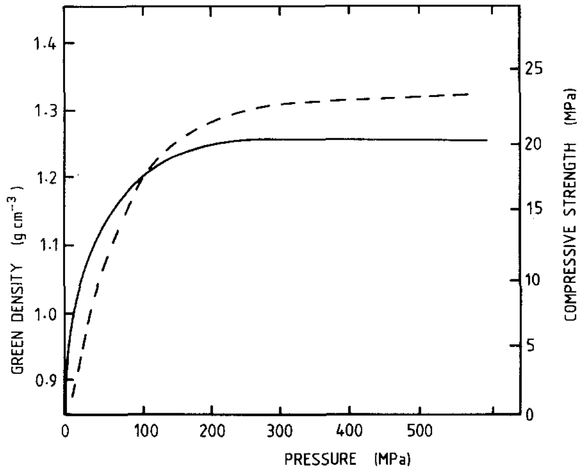

Figure 4 The relationship between (——) green density, (– – –) compressive strength and static pressure.

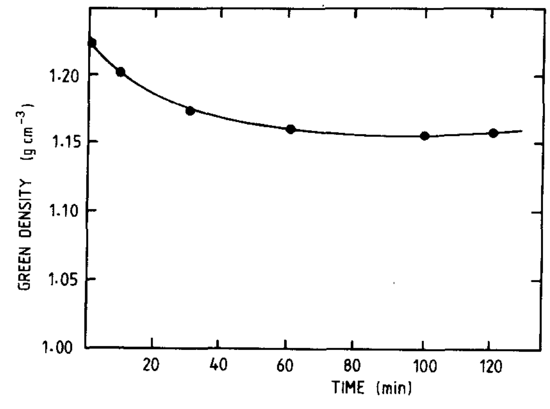

Figure 5 Relaxation of a static compact.

the experimental points having been omitted for the sake of clarity.

Quite apart from the respective levels of operative pressures the curves representing the variation of green density and compressive strength to fracture differ completely in the two cases. The explosive compact (Fig. 3) is characterized by an initial increase in both the density and strength with pressure, until an optimal condition is reached (about 10.5 GPa for this material) and by a rapid deterioration in these properties as the pressure is further increased. This pattern of behaviour is associated with three distinctive stages in the bonding and debonding of the material, present not only in polymers, but also in ceramics subjected to shock treatment [4, 8, 11].

In the first stage, up to a pressure of about 9 GPa in this case, only rearrangement of particles takes place with very little lattice distortion and plastic deformation present and, consequently, the conditions resemble those of static or isostatic compaction. In the second stage, with pressures ranging between 10 and 11 GPa, plastic deformation, some comminution of particles and bonding occur. Optimal conditions are thus reached. However, as the pressure is increased further, excessive fragmentation of the particles takes place, accompanied by damage to the compact caused by the release waves. Degradation of properties follows.

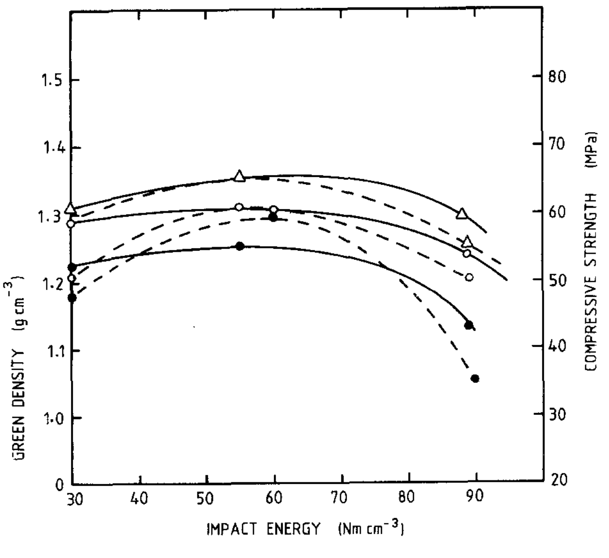

Figure 6 The effect of grain size on (——) the green density and (– – –) compressive strength of explosively compacted powder (conditions as in Fig. 3). (△) as-supplied, (●) $>200\,\mu$, (●) $<150\,\mu$m.

Static compaction (Fig. 4) results in an initial increase in the levels of both the density and strength but beyond a certain value of pressure (about 200 MPa for S57/116 powder) a saturation condition is reached and so further increase in the pressure is ineffective.

The essential lack of interparticle bonding, a characteristic of static and isostatic condition, often leads to a relaxation of the compact and its consequent loss of the original properties. A considerable reduction in green density of the PVC polymer investigated, is indicated by Fig. 5. It is only after some 3 h that steady state condition is reached and the density settles to a final value of 1.16 g cm^{-3}, as compared with the immediate post-compacting value of 1.22 g cm^{-3}.

3.3. Material characteristics and implosive compaction

3.3.1. Effect of particle size

The effect of the varying degrees of consolidation, noted earlier, is to affect the values of density and strength. This is illustrated in Fig. 6. For a given value of the supplied impact energy (corresponding to a specific value of pressure) the highest density and compressive strength are reached, respectively, when the as-supplied mixture is compacted. The lowest levels of these parameters are observed in the case of the + 200 μm fraction, with the – 150 μm range lying in between. In absolute terms, the maximum green density of the mixture is 96.4%, that of the – 150 μm fraction 92.8%, and the large grain fraction 89.3%. The corresponding strength figures are 65, 60 and 58 MPa.

The pattern of the curves reflects the three stages of compaction, discussed earlier, and the disposition of them is fully in line with the findings of Fig. 1.

3.3.2. Effect of tap density

For the given level of energy, the initial, pre-implosive, purely mechanical consolidation of the powder influences the final property of the compact. An increase in the tap density leads to a corresponding increase in the green density and compressive strength of the S57/116 (mixture) material (Fig. 7).

On the one hand, the higher pre-shock density implies that the energy supplied can be utilized in obtaining a higher degree of compaction, and, on the other, that the interparticle bonding is enhanced as a result of the increased areas of grain impacts. In consequence of this strength of the compact is increased. It is noted, in the case considered, that some 10% increase in tap density produces an increase of about 3% in green density at optimal conditions, but an increase of 16% in the higher range of energies where deterioration, due to fragmentation and release waves, sets in. The strength of the compact is correspondingly increased by 12 and 53%.

3.3.3. Effect of the container

Containment of the release wave and consequently a reduction in the debonding effect of the tensile stress system produced by the wave, is conditional on the

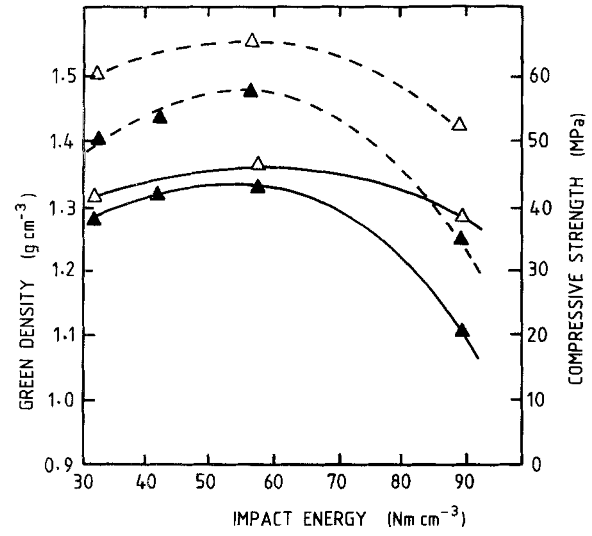

Figure 7 The effect of tap density in explosive compact (conditions as in Fig. 3). (——) Density, (- - -) strength; $\varrho_{\triangle} > \varrho_{\blacktriangle}$.

material and dimensional characteristics of the container. The influence exerted by these parameters on the final properties of the compact of the mixture is illustrated in Figs 8 to 10. The rigidity of the system increases with increase in the strength of the container itself, and, then, for the given material, with the increase in wall-thickness.

Fig. 8 shows the effect of the material referred to containers of 2 mm wall thickness. In terms of green density, the maximum value of about 1.35 g cm^{-3} is attained at the optimal energy level for copper of 22 Nm cm^{-3}, and that for steel of 65 Nm cm^{-3}. Impact energy of some 50 Nm cm^{-3} produces the optimal value in aluminium of about 1.28 g cm^{-3}.

In terms of strength of the compact, the steel container proves the most efficient in counteracting the effect of the tensile release wave. For the same set of optimal conditions, the strength increases from about 45 MPa for aluminium to 59 MPa for copper and 65 MPa for steel.

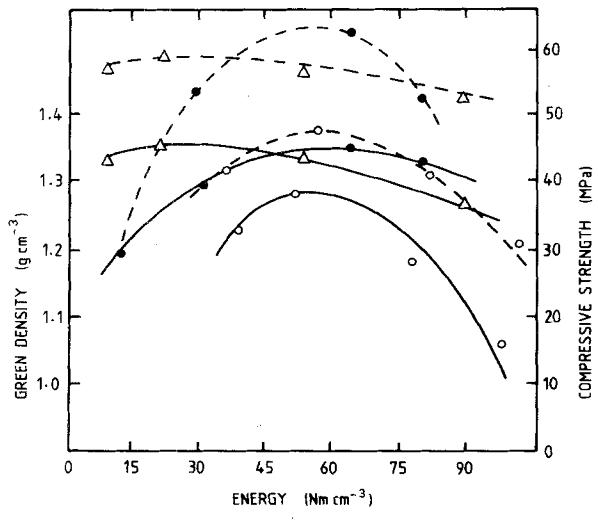

Figure 8 The variation of (——) green density and (- - -) compressive strength of an explosive compact with the material of the container (wall thickness 2 mm). (●) Steel, (△) copper, (○) aluminium.

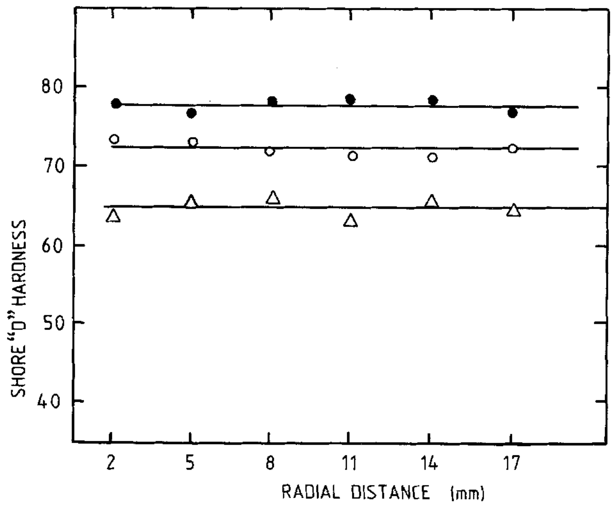

Figure 9 The effect of the container material on hardness of the explosive compact. (●) Steel, (△) copper, (○) aluminium.

This increased capacity for efficient bonding is also reflected in the levels of hardness measured across a plane section of the compact (Fig. 9). The highest levels of hardness correspond to compacts processed in steel containers and are followed by the copper and aluminium container systems. The difference between the extreme values, with the basically uniform hardness distribution amounts to some 25%.

As already indicated, for the given material, hardness level increases with the wall thickness. An example of this is afforded by Fig. 10 in the case of a steel container. It follows that higher values of hardness, green density and compact strength could be reached with thicker walled containers than those shown in Figs 8 and 9.

Creep tests, carried out on compacts manufactured in 2 mm thick-wall steel containers, gave quite satisfactory results. Fig. 11 shows the variation in strain/time curves at various levels of loading at the ambient temperature of 20° C, whereas Fig. 12 indicates the effect of temperature at a constant stress of 20 MPa.

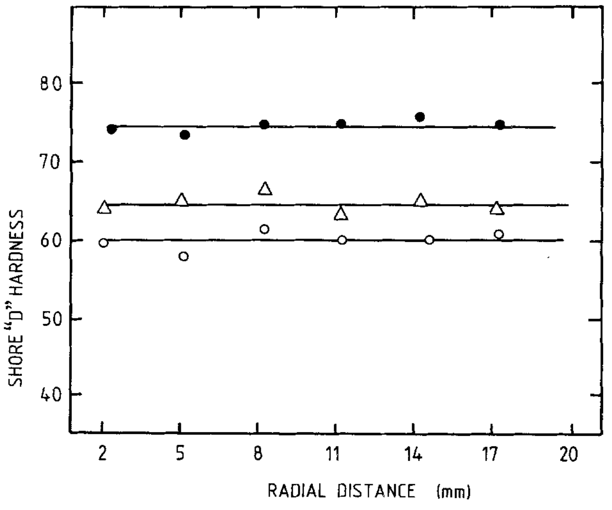

Figure 10 The effect of the wall thickness of a steel container on hardness levels. (△) 2 mm, (○) 3 mm, (●) 4 mm.

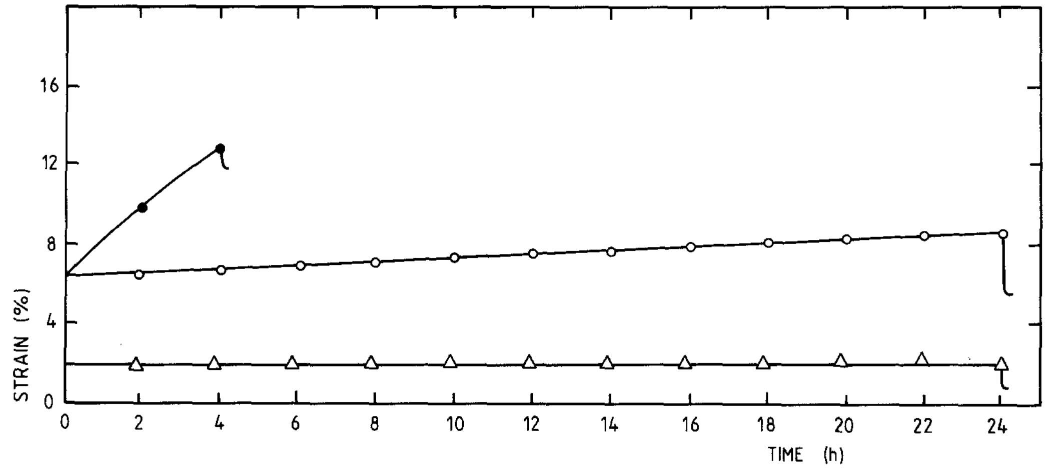

Figure 11 Creep characteristics of explosive compact at 20° C. (△) 20 MPa, (○) 40 MPa, (●) 50 MPa.

4. Conclusions

The response of a representative PVC particulate material to both static and shock treatment indicates clearly that interparticle bonding, present in an explosively consolidated specimen, results in considerably enhanced strength. The degree of bonding is, however, dependent on the particle size of the original aggregate, on the initial tap density and, finally, on the characteristic properties of the container. Efficient containment of the tensile release wave makes it necessary to opt for rigidity of the system when choosing the material and wall thickness of the metallic cylinder.

The high degree of densification and very satisfactory levels of strength and hardness of an explosive compact are indicative of the potential of this technique when considering industrial applications. The ability to form simple-shaped components from polymeric materials which would possibly, otherwise be difficult to process conventionally, makes the described approach attractive. This is particularly so because explosively manufactured compact can be safely machined to size and/or more complex shape.

References

1. R. A. PRÜMMER, in "Explosive Welding, Forming and Compaction" edited by T. Z. Blazynski (Applied Science, London and New York, 1983) p. 369.
2. R. A. GRAHAM, B. MOROSIN, E. L. VENTURINI, M. J. CARR and E. K. BEAUCHAMP, in "Metallurgical Applications of Shock Waves and High Strain-Rate Phenomena", Portland, Oregon 1985, edited by L. E. Murr, K. P. Staudhammer and M. A. Myers (Marcel Dekker, New York, 1986) p. 1005.
3. F. L. WILLIAMS, B. MOROSIN and R. A. GRAHAM, *ibid.*, p. 1013.
4. T. Z. BLAZYNSKI, *ibid.*, p. 189
5. T. Z. BLAZYNSKI and D. RAYBOULD, in "Materials at High Strain Rates", edited by T. Z. Blazynski (Elsevier, London and New York, 1987) p. 71.
6. A. A. HEGAZY, PhD thesis, University of Leeds (1985).
7. T. Z. BLAZYNSKI, A. A. HEGAZY and H. EL-SOBKY, in the Proceedings of the 8th International Conference on "High Energy Rate Fabrication", San Antonio, Texas 1984, edited by M. A. Myers and J. W. Schroeder (ASME, New York, 1984) p. 113.
8. A. A. HEGAZY and T. Z. BLAZYNSKI, *J. Mater. Sci.* **21** (1986) 4262.
9. A. A. HEGAZY, T. Z. BLAZYNSKI and H. EL-SOBKY, in "Mechanical Properties at High Rates of

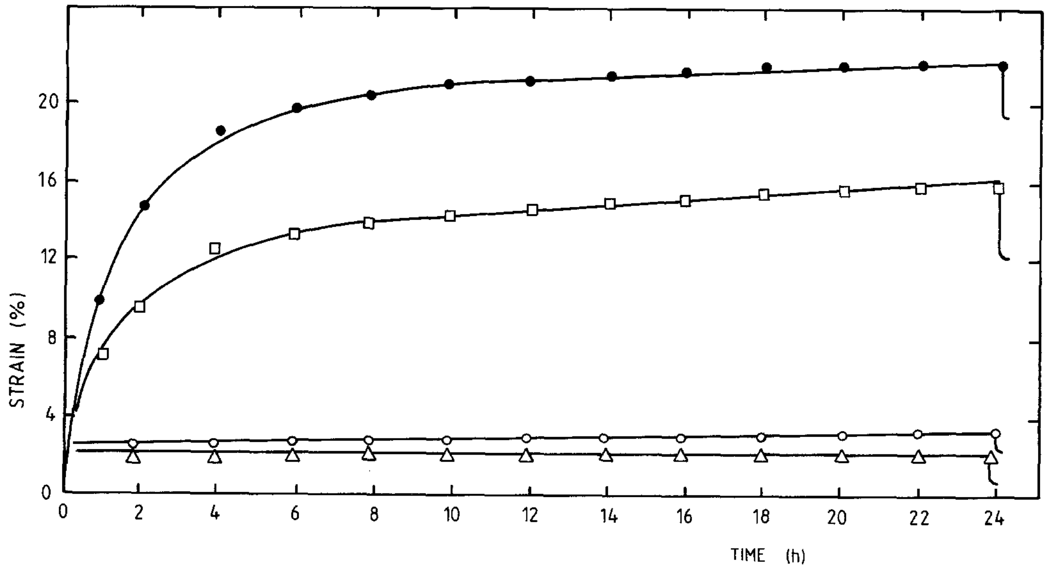

Figure 12 Creep characteristics of explosive compact at a stress of 20 MPa. (△) 20° C, (○) 55° C, (□) 70° C, (●) 83° C.

Strain, 1984", Oxford 1984, edited by J. Harding (The Institute of Physics, Bristol and London, 1984) p. 413.

10. C. HOENIG, A. HOLT, M. FINGER and W. KUHL, in Proceedings of the 6th International Conference on "High Energy Rate Fabrication", (Haus der Technik, Essen, FRG 1977) Paper 6.3.
11. R. A. PRÜMMER and G. ZIEGLER, *Powder Met. Int.* **9** (1977) 14.
12. A. B. SAWAOKA and T. AKASHI, "Summary of Studies on Shock Compaction and Shock Modification of Ceramics" (Centre for Explosives Technology Research, Socorro, New Mexico, USA, 1985).

Received 24 October 1986
and accepted 22 January 1987