

Starch Urea Formaldehyde Matrix Encapsulation of Solid Agrochemicals. I. Matrix Synthesis and Characterizations

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SYNOPSIS

A starch urea formaldehyde (starch-UF) matrix has been studied for application to the encapsulation of a solid insecticide. The pertinent parameters relating to the matrix synthesis have been identified and the influences of these parameters on release of the insecticide from the starch UF matrix have been investigated. The key parameter controlling the rate of release is the urea to starch ratio. It is shown that the release process can be described in terms of the generalized equation $M_t/M_\infty = kt^n$ where k and n vary with system variables.

INTRODUCTION

Controlled release (CR) of agrochemicals through a polymer matrix is an area of significant practical and scientific interest. CR formulation based on a new polymer matrix made of starch crosslinked by urea formaldehyde prepolymer (starch-UF) has been developed.¹ The matrix has been used for encapsulating a systemic solid insecticide, carbofuran, and the CR formulation has been extensively field tested for bioefficacy.²

Carbofuran (2,3-dihydro-2,2-dimethyl-7-benzofuranyl-*N*-methyl carbamate) is a broad spectrum insecticide used for protecting a large number of crops. It is applied as granules around the plants at a very early stage of growth; the initial application is followed by periodic applications over a protection period of 40–70 days depending on the crop. It is unstable in alkaline media. By encapsulating it in a polymer matrix, it was expected that its persistence could be enhanced so that a single application would protect the plant for the entire season.³

Starch is an abundant, naturally occurring, biodegradable polysaccharide found in the plant kingdom and is cheaper than any synthetic polymer. It contains free hydroxy groups and can easily be derivatized. Shasha and coworkers^{4–8} have used several

starch derivatives to encapsulate various pesticides. Except for autoencapsulation⁷ or spray application⁸ procedures, the other methods of encapsulation required derivatization in alkaline media in which most of the carbamate or organophosphate pesticides are unstable. The starch-UF system on the contrary has the twin advantages of 1) a wide variety of release rates and 2) an encapsulation process under neutral and acidic conditions under which the pesticides are stable.

In this paper, we report the results of a study on the synthesis of a starch-UF matrix encapsulating carbofuran. Several matrices with different urea to starch weight ratios (U/S), formaldehyde to urea molar ratios (F/U), and active agent loading (a.i.) were prepared to study the effect of these parameters on the release pattern of carbofuran. Data obtained were analyzed to formulate a probable release mechanism. A simple mathematical model describing the release of carbofuran from a starch-UF matrix is presented in a companion paper.

EXPERIMENTAL

Materials

Urea (chemically pure, Glindia), formaldehyde (S.D. Fine Chemicals, 37% w/v solution in water), formic acid (Loba), maize starch (Anil Starch Products), and sesame oil (Ahmed Oil Mills) were

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used as such. Technical carbofuran (75–80% a.i.), a gift from Rallis India Ltd, was also used as received.

Synthesis of the Starch-UF Matrix

Four major steps are involved in synthesizing the starch-UF matrix encapsulating carbofuran. These are: (a) Synthesis of urea-formaldehyde prepolymer, b. Coating carbofuran with oil (b) (c) Reacting UF prepolymer with gelatinized starch in which oil-coated carbofuran had been dispersed (d) Wet-sieving and curing to get rigid, crosslinked granules.

Synthesis of UF Prepolymer. Extensive patent literature is available on the synthesis of UF prepolymer, with formaldehyde to urea molar ratios (F/U) from 1 to 4 and using both acid and alkali catalyst.⁹ At F/U values beyond 2.0, premature turbidity and gelling takes place. Conditions were optimized when F/U equals 1.5, as the release profiles are not materially different between 1.5 and 2.0. The typical method for synthesizing UF prepolymer having F/U value of 1.5 is as follows:

Two hundred milliliters of aqueous formaldehyde solution (37% w/v) is taken in a 250 mL round-bottomed Flask and its pH is adjusted to between 8 and 8.5 with a few drops of dilute NaOH, followed by the addition of 2 drops of triethanol amine. Urea (100 g) is then dissolved in the flask and the resulting solution is gently refluxed for 15 min, at which point its viscosity increases, and it is then allowed to cool. A clear solution is usually obtained. If the pH is less than seven and turbidity develops the solution should be discarded.

Coating of Carbofuran with Oil. Technical carbofuran is a fine powder (size 5–10 μm) with 75–80% a.i. content. It has a solubility of \sim 1200 ppm in water at 35°C. Direct dispersion of this powder in gelatinized starch leads to dissolution and recrystallization at the surface causing high initial release: a burst effect. A hydrophobic coating of the particles was found necessary to reduce the burst effect. After trying several hydrocarbon and fatty oils, sesame oil was found to be the most effective, presumably because of its ready coverage and wettability of the particle surface. Sesame oil in the amount of 25% by weight of carbofuran was found suitable for this purpose. It was thoroughly mixed with carbofuran so that all the particles are coated and there is no lump formation.

Gelation, Dispersion, and Encapsulation. Maize starch (100 g) is dispersed in 300 mL of water and

gelatinized by stirring and heating on a boiling water bath until a transparent paste is obtained. The paste is placed in a Hobart mixer and 9.6 g of technical carbofuran coated with 2.4 g of sesame oil is added to it with constant agitation so that the carbofuran particles are evenly distributed. The UF prepolymer solution (prepared as described above) is then slowly added with agitation, followed by dropwise addition of formic acid solution until the pH reaches 3.0. The agitation is continued for 10 min more as the paste slowly turns rubbery and finally crumbles to a crosslinked swollen mass.

Wet Sieving and Curing. Wet sieving of the above mass through a suitable mesh screen followed by drying will give hard granules with particle size in the desired range. The effects on the release profile of curing (drying) at different temperatures (50–80°C) and for different periods (2–6 h) were studied, and the conditions were optimized to 50°C and 4 h, as higher temperatures or longer periods of curing did not materially affect the release profile. The wet mass from the encapsulation is sieved through a 10 mesh screen and the soft granules cured in air draft oven at 50°C for 4 h. The yield of the dried product is 249 g.

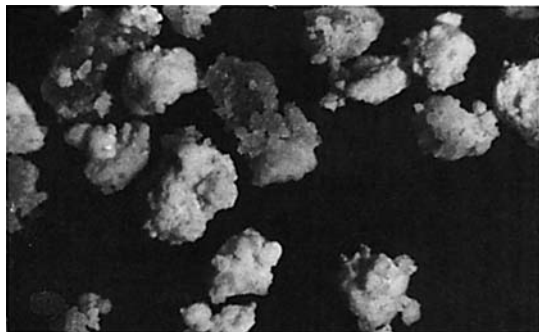
Figure 1 shows the micrographs of the matrix prepared in the manner described. The shape of the matrix, as can be observed from Figure 1, is neither spherical nor planar. The size typically ranges between 700 and 2000 μm .

Characterization of Starch-UF Matrix

The CR carbofuran granules are characterized by their a.i. content and release profiles.

Active Ingredient Loading (a.i.) Content. Carbofuran shows maximum absorbance at 278 nm, and obeys the Beer Lambert law in the concentration range of 10–100 ppm. The concentration of carbofuran in solution could hence be determined by measuring its absorbance at 278 nm using a Hitachi 220 UV-VIS spectrophotometer, after preparing a calibration curve with standard solutions, or by using a JASCO HPLC.

Carbofuran could be fully extracted by refluxing with 50% aqueous methanol in which the granules readily swell. Dry CR granules (1.0 g) are refluxed with 100 mL of 50% aqueous methanol for 4 h. The granules are then filtered and washed with the solvent mixture. The filtrate and washings together are made up to a known volume and the absorbance at 278 nm is measured for computing the a.i. The a.i. content of the product from curing is found to be



Magnification - 8



Magnification - 20

Figure 1 Micrographs of the matrices.

3%. This product has been prepared with F/U ratio of 1.5 and U/S ratio of 1.0.

In Vitro Release Measurements. The solubility of carbofuran in water is about 1200 ppm at 35°C. In order to maintain perfect sink conditions, release studies were carried out with a.i. levels such that the resulting carbofuran concentrations would not exceed 50 ppm which is less than 5% of the saturation level in water. Distilled water (500 mL) is placed in a tablet dissolution vessel maintained at $35 \pm 0.1^\circ\text{C}$, provided with a paddle stirrer, and stirred at a constant speed of 150 rpm with a sufficient quantity of dry granules to conform to a total a.i. level of 25 mg. Aliquots of 10 mL of the supernatant solution are withdrawn by a pipette at pe-

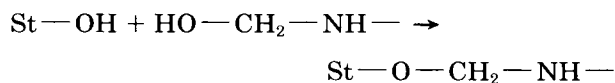
riodic intervals, and the carbofuran content is computed from its absorbance at 278 nm. The vessel is replenished each time with 10 mL of distilled water so that its overall volume is maintained at 500 mL. The release profile is then plotted as the percentage release versus time. Particles in the size range of 0.7 to 2.0 mm, obtained by sieving (-10 + 25 mesh) were used for the release studies.

RESULTS AND DISCUSSION

Table I gives the matrix parameters studied in the present investigation. The yield and the measurement of a.i. values indicate that over 98% of the carbofuran is accounted for.

Figure 2 shows the release pattern in terms of fractional release versus time for variation in U/S from 0.2 to 1.0. It should be noted that the slopes of these plots at various time will yield the corresponding release rate. There is a marked decrease in release profile with increase in U/S value from 0.2 to 0.6. The release rate is lowest at U/S value of 0.6 above which it is once again higher. The ratio of U/S is a measure of the degree of crosslinking. The extent of crosslinking in the matrix at higher U/S values is higher and as a result the effective diffusion coefficient of carbofuran in the matrix decreases with increase in U/S values.

The urea-formaldehyde prepolymer contains methylol groups ($-\text{NHCH}_2\text{OH}$) which, in the presence of acid, react with the $-\text{OH}$ groups of starch molecules leading to a three dimensional network under proper stoichiometric conditions.



However the starch-UF system is quite different from conventional crosslinked polymers. The urea to starch (U/S) ratio used in this work gives 0.60 to 3.0 moles of methylol per mole of anhydroglucose in the starch. Thus the structure is expected to be more of a ladder type or an interpenetrating network than a conventional crosslinked polymer. Even un-

Table I Matrix Parameters

| Parameters | Range |
|---------------------------------------|-----------|
| Urea/starch (U/S) (weight ratio) | 0.2-1.0 |
| Formaldehyde/Urea (F/U) (molar ratio) | 1.5 |
| Active agent loading (a.i.) | 3.0-20% |
| Curing schedule | 50°C, 4 h |

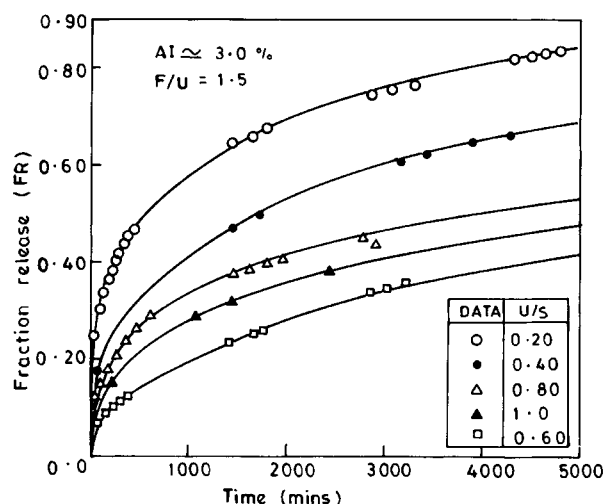


Figure 2 Fractional release of carbofuran from starch-UF matrix prepared at different U/S ratios.

der these conditions, there is an increasing trend towards tightening of the crosslinked structure up to a molar ratio of ~ 2.0 (at U/S value of 0.6, the molar ratio works out to 1.84) beyond which there is obviously no further crosslinking reaction, but only increased self-condensation of the methylols. Thus the system with the U/S value of 0.6 appears to be both unique and the most efficiently encapsulating on the basis of its having the lowest release profile. The observed anomaly of increased release rate at higher U/S value may be due to microvoids and cracks produced by the rigidification of the matrix at high levels of urea resin content. Evidence in support of chemical linkage between starch and UF methylols has been recently obtained¹⁰ from solid state ¹³C NMR studies of the matrix. Figure 3 shows the release pattern at three different a.i. levels at the optimum U/S value of 0.6. The drop in fractional release with increase in loading from 3 to 10% can be explained in terms of the simplified Fickian derivation of Paul and McSpadden¹¹

$$Q_t = [2D_e C_s (C_a - C_s) t]^{1/2} \quad (1)$$

where Q_t is the amount released per unit area at time t , D_e is the effective diffusion coefficient of the agent in the polymer, C_s is the solubility of the agent in the polymer, and C_a is the total concentration of agent in matrix. This expression reduces to

$$Q_t = (2D_e C_s t)^{1/2} C_a^{1/2} \quad (2)$$

when $C_a \gg C_s$, as is the case for the present system. Thus Q_t/C_a , which is a measure of fractional release,

will be inversely related to $C_a^{1/2}$ or, in other words, fractional release will decrease with increase in loading. However when loading is further raised to 20%, the matrix becomes porous leading to much faster fractional release, almost to the extent of 3% loaded system. Evidence for the porosity at high loading is discussed elsewhere.¹²

The release of solid agent dispersed in a polymer matrix has been addressed by Higuchi¹³ using mainly Fick's laws of diffusion. He has arrived at a \sqrt{t} relationship for the release profile from a planer device. Ritger and Peppas¹⁴ have introduced a simple power law type equation

$$M_t/M_\infty = kt^n \quad (3)$$

to discuss the general solute release behavior of polymeric devices, where M_t/M_∞ is the fractional release at time t , k is a constant, and n is the diffusional exponent characteristic of the release mechanism. They have shown that this equation can adequately describe the release of agents from slabs, spheres, cylinders, and discs, regardless of the release mechanism. According to their model, in the case of pure Fickian release the exponent n has limiting values of 0.50, 0.45, and 0.43 for release from slabs, cylinders, and spheres respectively. This coincides with Higuchi's model for the planer device.

The starch-UF system consists of irregularly shaped particles (see Fig. 1) in the size range of 0.7 to 2.00 mm ($-10 +25$ mesh) which do not fit into any of the above models. Nevertheless, as an approximation, if we assume the particles to be spherical we can draw some conclusions based on the Ritger and Peppas model. In the case of a polydisperse spherical particulate system, their model predicts

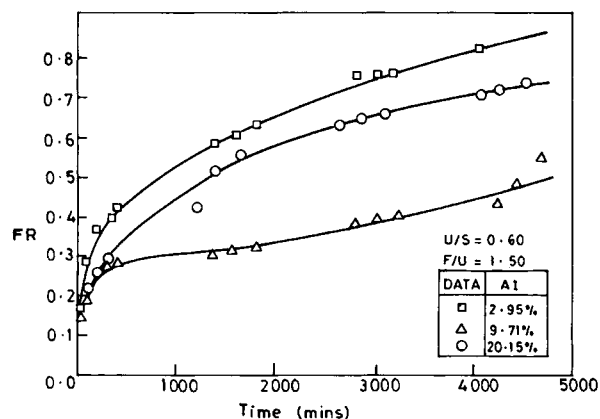


Figure 3 Fractional release of carbofuran from starch-UF matrix with two different a.i. contents.

Table II Release Rate Constant k and Diffusional Exponent n for St-UF Carbofuran Samples at Different Loadings

| % a.i. | $k \times 10^2$ (min) ⁻¹ | n | Correlation Coefficient, r |
|--------|--|--------|---------------------------------|
| 2.95 | 6.73 | 0.2971 | 0.9910 |
| 9.71 | 5.71 | 0.2454 | 0.9800 |
| 20.15 | 5.21 | 0.3106 | 0.9982 |

varying n values for Fickian diffusion depending on the width of distribution. In fact for a particular hypothetical distribution, they have computed as low a value of n as 0.3 for a Fickian diffusion. The release data of St-UF samples having the optimum U/S value of 0.6 and at the three levels of loading were analyzed in terms of the above generalized equation for obtaining the corresponding k and n values (Table II). The n values of 0.29, 0.25, and 0.31 respectively are quite consonant with the values for an irregularly shaped polydispersed system. The release mechanism could be Fickian at U/S = 0.6, but this requires further confirmation. The n values at other U/S ratios and at other pHs were found to be substantially different than 0.3 and such a difference can be attributed to the phenomena of swelling and erosion. Furthermore the parameters k and n vary with the system variables and therefore the release equation can at best be taken as semiempirical in nature.

In the companion paper, a release model for the present system has been developed for a fast-swelling and slow-eroding matrix resembling the real system.

CONCLUSIONS

The technique of synthesis of a starch-UF matrix encapsulating carbofuran has been standardized and the key parameter controlling the release rate is identified as the U/S ratio. It is shown that the release process can be described in terms of the gen-

eralized equation $M_t/M_\infty = kt^n$ where k and n depend on many system variables.

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