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The Effect of Secondary Fiber Furnish on the Tensile Energy Absorption Capacity of Paper Under Repeated Extension Cycles

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THE EFFECT OF SECONDARY FIBER FURNISH ON THE TENSILE ENERGY ABSORPTION CAPACITY OF PAPER UNDER REPEATED EXTENSION CYCLES

by

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ABSTRACT

The object of this study was to determine what effect does recycling paper have on the tensile energy absorption (TEA) of that paper. The TEA of the sheet was split into two components, the elastic and the plastic. The sum of the two components gives the composite TEA.

The TEA's were measured at three different numbers of extension-cycles. It was found that a greater number of extension cycles resulted in greater TEA's for both elastic and plastic regions.

It was discovered that elastic TEA does not decrease with the first or second degree of recycling. Plastic TEA suffers its greatest losses after the first and second recycles.

Further work is needed to investigate which fiber properties are responsible for certain losses in TEA. There is also a need to study the effects of ink removing chemicals, and dynamic sheet formers, on the physical characteristics of recycled paper.

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INTRODUCTION

With the increasing costs of wood and pulp, more and more paper and board manufacturers are looking toward recycled paper as a possible cellulose fiber source. The low cost of using recycled paper stock can be associated with other desirable and profitable consequences. The elimination of the pulp mill or at least the reduced need for expanding pulp production capability is one example. From an environmental viewpoint the recycling of paper is also very attractive. Perhaps one of the most important considerations is that in the future all of the benefits of recycling paper will become more and more dominant in the paper industry.

Unfortunately there are very many problems to be overcome, in the utilization of secondary fibers. Collection of waste paper is a large problem, with many social, cultural, and economic hang-ups. Technological problems are abundant. By the time waste paper is collected, decontaminated, and made into a usable form of pulp, a great deal or maybe all of the economic incentive is lost.

As time goes on many of the technological problems will be solved, and the economic incentive will increase. Therefore many paper makers will start adding secondary fibers to their stock chests and they will want to know the resultant effects on their product.

Some studies have already been done on the effect of using secondary fibers in paper. Many paper and board manufacturers have been recycling paper and using it in their product for a long time. However, both the production and the investigation of secondary fibers needs to be expanded, so that they may be utilized in greater and more diverse quantities.

The goal of this study is to try and determine more specifically, what effect does the recycling of paper have on the stress-strain properties of that paper. The focus will be on the changes which occur in the plastic and elastic portions of the stress-strain curve and how these changes affect the TEA capacity of the paper.

THEORETICAL DISCUSSION

Most studies on the effects of fiber reuse have had severe limitations. A typical short-coming is the lack of handling or use, of laboratory handsheets. Quite often handsheets are made, dried, and repulped. Obviously this method is not at all analogous to a realistic fiber life-cycle. This type of study may be useful in determining the effects of drying, rewetting, and slightly cutting and fibrillating the wood fibers which go into a new sheet. The limitations of this method are further restricted by the use of a static, laboratory, handsheet making device. This type of study is not intended to be representative of a real, paper mill situation.

Another major difference between the laboratory study of secondary fiber use effects and the paper mill effects, is that the laboratory typically uses a single type of high quality stock, whereas many paper mills utilize a less expensive, lower quality stock.

Only a few articles have been published concerning the effects of secondary fibers on paper properties. In one of them Cildir and Howarth (1) performed a study of the effects of fiber reuse on paper "strength". Their study was two-fold in the sense that they identified and confirmed certain properties from two categories of handsheets. One category was composed of fibers that were all recycled the same number of times, and used in a single sheet. The other category was made from a blend of once recycled, twice recycled, etc., fibers all blended into the same sheet. All handsheets were made from stock which was beaten to the same freeness.

Their results were that tensile strength decreased (35% after four repulpings) rapidly with each repulping, at a decelerating rate. After approximately the sixth recycle they reached a stable level.

Elongation in this study was found to initially decrease with repulping. After the second repulping the elongation did begin to increase, but at a much slower rate than the initial decrease. Their virgin sheet had an elongation of 3% where as the twice repulped sheet had only 2% elongation.

In order to try and pinpoint the reason for these decreases, a zero span tensile test was run. The results showed that the fibers did not lose strength and therefore the loss in strength was due to changes in bonding. They could not explain whether there was a reduction in bond area or a reduction in individual bond strength.

A similar study was performed by McKee (2) where the effects of refining were given more attention. McKee also used a correlation between apparent density and bonding. It was shown that repulping decreases the apparent density which is indicative of less bonding. The decrease in bonding is the primary reason for losses in tensile strength. After six repulpings the tensile strength had decreased 30%.

In his study, fiber strength was checked to see what changes may have occurred. Fiber strength decreased by 21% after six repulpings.

This decrease in fiber strength was still small compared to the 70% decrease (after six repulpings) in transverse bond strength.

Both bonded area and individual bond strength are important in contributing to transverse bond strength. Therefore light scattering measurements were made to detect any changes in bonded area. The results indicate that bonded area does not decrease significantly and that therefore decreased individual bond strength must be the critical factor in explaining the decrease in tensile strength. Some doubt was cast over this conclusion by some recent evidence, which McKee mentioned, that the light scattering technique was not reliable.

McKee's study also showed a decrease in elongation with repulping. The losses in elongation after each recycle were decreasing and seemed to be stabilizing around 20% (lost) after the sixth recycle.

Some of the desirable characteristics of paper, which had been diminished from recycling, were recovered after extra refining. The amount of recovery potential was affected by the amount of refining the fiber had undergone previously.

The tensile strength of recycled paper did not improve with increased refining of the original virgin stock. Elongation was slightly effected by refining. More refining of the virgin pulp caused decreases in stretch, for both virgin sheets and recycled sheets.

The tensile energy absorbtion (TEA) also decreased with increased refining. The rate of decrease however was not as great as for virgin pulp.

McKee notes that fiber swelling decreased continually after each repulping cycle. This loss in "swellability" gives a decrease in fiber surface area. This makes it more difficult for fibers to bond to one another.

Another viewpoint, with the same conclusion, is given by Horn (3). He found that fibers undergo "hornification" (hardening) when they are dried out. So as the sheet is repeatedly rewetted and redried the fibers become harder and stiffer. This loss in fiber flexability results in poorer bonding capability.

Horn found that with strong sheets (virgin pulp) more fiber rupture took place than with the weaker, recycled sheets. Fiber strength decreased with repulping but became stable after the second recycle.

Horn's findings confirm the theory that adverse effects on fiber-fiber bonding is the predominant factor in the loss of tensile strength.

The modulus of elasticity was found to increase with recycling. This finding reflects the increased stiffness caused by the hardening of fibers which have been recycled. Increases in length of the elastic segment of a stress-strain curve may provide a method of qualitatively predicting the amount of secondary creep or mechanical conditioning which the paper will exhibit. Van den Akker (4) states that paper which is strained well into the plastic regime will have a more linear and extensive elastic region upon subsequent load cycles. Perhaps an increase in the length of the elastic region will be related to the amount of plastic flow or secondary creep which will be found in a recycled sheet. The TEA should also be affected by any changes in the amount of secondary creep caused by mechanical conditioning.

Reasons explaining, or predicting the changes in paper rheology, are often related to changes in the fibers. From variations in fiber length, strength, diameter, cell wall thickness and many other fiber characteristics, come the variations in sheet characteristics.

Fiber length distribution is an important factor in sheet properties. It is generally accepted that long fibers make stronger paper. Short fibers are also necessary, because they fill in the voids and make the paper denser. A shift in a fiber distribution curve, which favors long or short fibers, will produce paper that has different properties. Recycling has the tendency to shorten fiber length. Fiber debris and fines content is also increased, due to the reswelling reshrinking and mechanical agitation which secondary fibers undergo. Decreases in strength are strongly associated with the increase in fines content, and a shorter fiber distribution, incurred by the recycling of fiber (5).

Fiber-to-fiber bonding has already been mentioned as the predominate factor concerning tensile strength. It is also important when considering elongation, creep, and TEA. Bonding potential is affected by many intrinsic characteristics of the fiber. Swelling was mentioned as being important to bonding, because it changes the surface area.

Swellability, in turn, is dependent on even more intrinsic fiber characteristics. The chemical composition of the fiber will effect the molecular forces which inhibit the swelling of a fiber. Removal of lignin will improve swellability. Hemicelluloses are largely responsible for fiber swelling, therefore removal of them will reduce swelling (6). There is no information in the literature mentioning whether the chemical composition of a wood fiber is changed by the laboratory recycling process. It would seem likely, in view of the decreases in swellability, that changes do occur.

Swelling will also make the fiber more flexible, which increases the bonding potential.Flexability is also related to fiber wall thickness. A thick wall of cellulose will make the fiber less flexible and less easy to collapse than a thin walled fiber. There is no information concerning whether or not fiber wall thickness is changed significantly when fibers go through the recycling process.

Fiber strength has a pronounced influence on the tensile strength of a "strong" sheet of paper. In weak paper fiber strength is of little consequence (7). Although the literature shows that fiber strength decreases by as much as 5% after one recycling (2), it still does not control the stress-strain properties of a paper sheet.

All of the mentioned strength factors will have a great deal of influence on rheological properties. There are additional factors though which do not have an observable effect on strength but which do effect the load-deformation characteristics. Fiber rheology is a fundamental trait of each fiber which will effect the macroscopic reaction of paper under stress. Fibers are viscoelastic in nature. Differences in the stress-strain relationship can be expected between latewood and early wood fibers, as well as between species, environment, and herditory factors (8).

It has been suggested that superficial (invisible) microcreping is responsible for nonrecoverable creep, or plastic TEA (9). The main idea is that when the sheet is strained the microcreping comes out. More will be mentioned on this fiber property later.

Other factors which effect sheet rheology but are not fiber properties are sheet formation, structure, and test conditions. Test conditions include both internal conditions such as rate of loading, and external conditions such as temperature and humidity. These factors are usually controlled by instrumentation and standardized procedure.

There are different theories concerning the rupture mechanism of paper under stress. There are two main schools of thought, which if united, qualitatively explain the mechanism. One of the theories has been put forth by Rance (10). He suggested that during the straining of paper, certain fiber to fiber bonds are broken. As these bonds are broken the structure of the paper changes, so as to accomodate the stress. This concept explains the phenomena of irreversible creep in the plastic region of a stress-strain curve, and it also takes into account the known structure of paper.

Another theory which is put forth by Steenberg (11) tries to explain the stress-strain relationship with various spring and dashpot models. He also suggested that fibers have superficial (invisible) microcreping, and that as paper is strained the microcreping is taken out. This theory does not have the support of known fiber structure and is purely hypothetical. It does however give some explanation of the elastic and viscous nature found to exist in fibers. These two theories combined express the idea that during the straining of paper, energy is dissipated to the fiber as well as the fiber to fiber bonds.

More modern theories, which attempt to be more quantitative in their approach, utilize both of these concepts. Van den Akker (4, 12) has developed a theoretical model which uses a Cartesian co-ordinate system to be used in mathematically relating position, angles, torsional forces, and shear forces of a fiber in a sheet of paper. Mathematical functions are used profusely to account for orientation, segmental length distribution, and fiber-fiber bond rotations. Even in simplified form these theoretical relationships involve series of quadruple integrals. Similar models, with their theoretical relationships, have been offered by Corte and Kallmes (13). None of these theories have been worked out to the point where the stress-strain relationships of a given sheet of paper can be predicted using the basic parameters of fiber characteristics. Maybe in the future these equations will be solved and become useful in designing paper.

In the meantime, each fiber parameter must be studied independently to be able to understand the role of that or those parameters. In the case of recycled fibers one must analyze the change in fiber length distribution, fiber strength, bonding, and chemical composition. Changes in these parameters can be observed in the physical properties of the paper sheet. Thus for example, a study of fiber reuse on the TEA capacity of a paper sheet under repeated extension cycles can be related to changes in fiber characteristics.

One might expect that with lower bonding capability for secondary fibers, the plastic region of a stress-strain curve would be smaller in area. The microcreping theory would suggest that shortened, hardened fibers would give less elastic type stretch and therefore put more strain on the fiber to fiber bonds. The overall effect would give a decrease in TEA, as the literature states, but as to what areas are under the plastic and elastic segments and how each area is changed with reuse is of interest.

With more information secondary fiber may be more successfully utilized in different areas of the paper industry. The secondary fiber may become more than a virgin pulp substitute, and be recognized and used for its own particular characteristics.

EXPERIMENTAL PROCEDURE

Bleached kraft, softwood fibers were beaten in a laboratory size Valley beater. Beating was continued until the Canadian Standard Freeness was at the 500 level. Handsheets were made from this stock, on a Noble & Wood Handsheet machine. Nine handsheets, weighing 2.50 $\pm$ .06 g were selected for testing on the Instron. Three of these sheets were subjected to a seven extension-cycle rupture test. Three more handsheets were subjected to the same test using only five-extension cycles. The final three sheets were subjected to three extension cycles. Stress-strain curves and area integrator data were collected for analyzation.

All of the handsheets which were not selected for testing, were soaked in distilled water for 24-48 hours. After soaking, the sheets were disintegrated and beaten in the Valley Beater, until the freeness was approximately 500 CSF.

This recycled stock was then used to make a new batch of handsheets. The technique was identical to the one used in making the virgin handsheets. Again, nine samples were selected, weighing 2.50 g $\pm$ .06 g, and subjected to the same type of extension-cycle testing as before.

The process of testing samples on the Instron and using the remaining sheets for a new generation of handsheets was repeated until five orders of recycled paper (or six types of paper) were produced.

It should be realized that as the paper was recycled, its' tensile strength and stretch capability decreased. Thus it was necessary to change the amount of elongation which the various levels of recycled paper were subjected to. For example, virgin paper, in a five extension-cycle test, was stretched .25, .30, .35, .40, .45, cm successively. Paper which had been recycled four times was stretched .15, .20, .25, .30, .35 cm successively. The fact that these two types of paper have undergone different amounts of elongation does not destroy the legitimacy of comparing their stress-strain curves. It does add another variable which prevents the forming of some detailed conclusions. There are still some general conclusions however which can be drawn and are presented in the section on discussion of results.

There was another anomaly in procedure in this experiment. In some cases the samples ruptured before or after the completion of the final extension-cycle. In these cases, the lack or excess of an extension cycle was considered to be a property of the sheet and was therefore included in the analysis of data from that handsheets group.

Procedure for Analyzing Data

The integrator which was used in conjunction with the Instron Tensile Tester was able to give a value which was related to the area under the stress-strain curve. This area corresponded to the amount of work done on the sheet or the amount of energy absorbed by the fiber network.

The area under the stress-strain curve was divided into two portions, elastic and plastic. The elastic area is that area which lies below the line which is used to measure the modulus of elasticity. This area is in the form of a triangle and can be calculated by measuring the base and height of the triangle.

The remaining area constitutes the plastic section. The plastic area can be determined by subtracting the elastic area from the composite area. The composite (plastic and elastic) area is the total area which has been determined by the integrator.

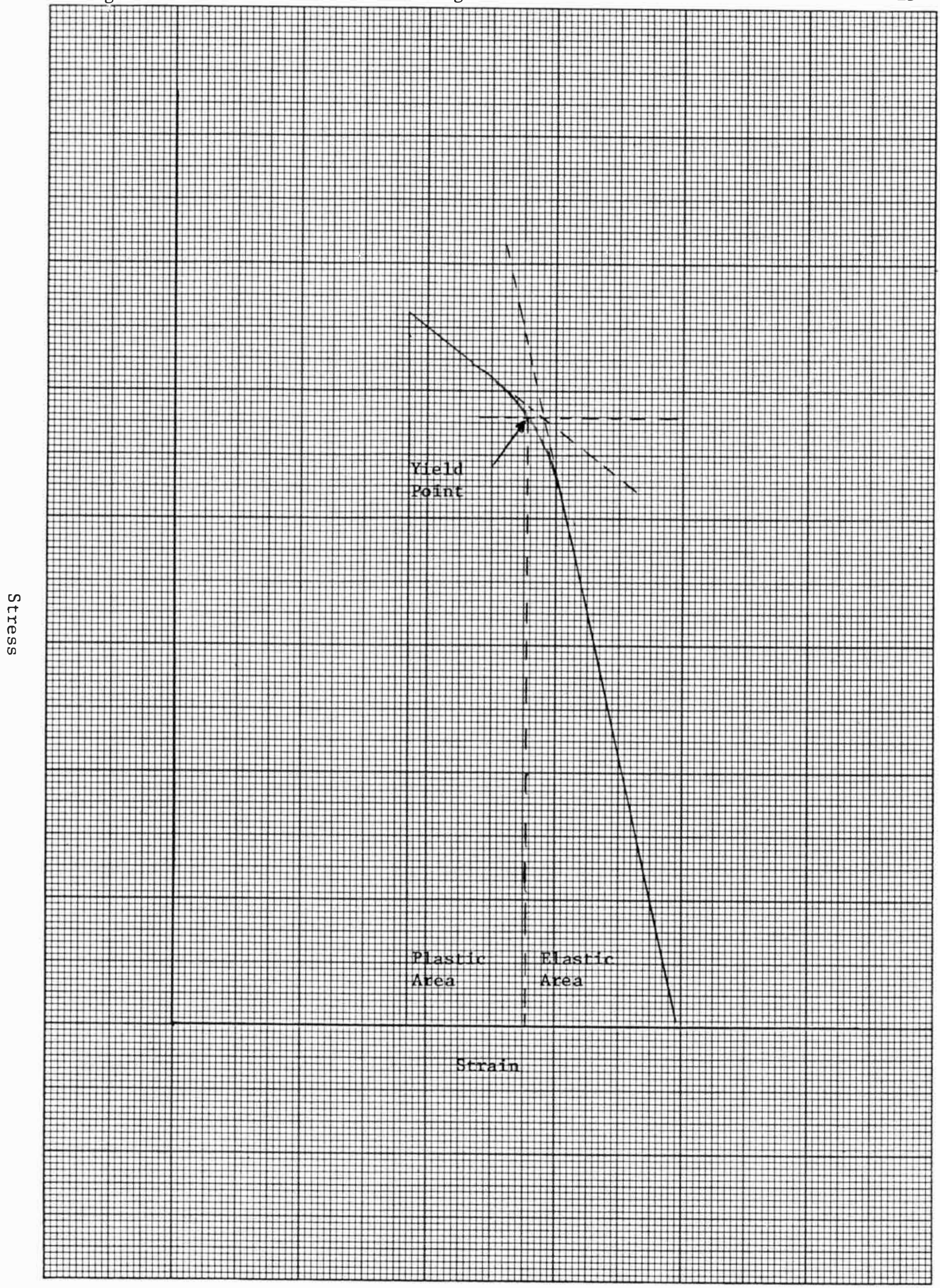
In many cases the distinction between plastic and elastic areas was not readily determined. In these cases, the yield point was not sharp. Therefore a procedure was used to construct an approximate or average yield point. This procedure can be best explained by the following diagram.

The method is to construct a line which is coincident to the elastic segment. Another line is constructed which is coincident to the plastic segment of the stress-strain curve.

The intersection of these two lines gives a point whose y-coordinate will intersect the stress-strain curve at the approximate yield point (Figure 1).

Once the yield point has been determined, the stress can be easily separated and converted into tensile energy absorption. The tensile energy absorbed can then be used to directly compare and evaluate the different types of handsheets and the different levels of extension-cycling.

Figure 1: Procedure for Determining the Yield Point



RESULTS PRESENTATION

Data was taken from the stress-strain curves for each extension cycle. The composite, elastic, and plastic areas were calculated and converted to TEA. The TEA's for every sample were added up to give the total TEA's required to rupture the sample (i.e., the plastic TEA for each extension cycle of a certain specimen were added together to give the total plastic TEA). The same procedure was used for the elastic and composite TEA's for that sample. Each figure in Table I is the mean average of three samples. The data has been divided into three groups, each group had been extended seven, five or three times before rupture. Each number represents a TEA for that type of paper and that number of extension cycles.

Graphs have been constructed for showing the relationship between TEA and degree of recycling.

TABLE I

SEVEN EXTENSION CYCLES

Degree of Recycling	0	1	2	3	4	5
Total Elastic TEA	3764	3648	3617	2636	1793	1403
Total Plastic TEA	4283	3360	2524	2135	1164	1170
Total Composite TEA	8048	7008	6141	4771	2957	2573
FIVE EXTENSION CYCLES						
Total Elastic TEA	3355	3252	1741	2578	1569	1373
Total Plastic TEA	4333	3247	1715	2150	1359	1051
Total Composite TEA	7688	6499	3456	4728	2928	2424
THREE EXTENSION CYCLES						
Total Elastic TEA	1896	2098	1569	1256	749	831
Total Plastic TEA	4368	2782	2332	2139	1291	1071
Total Composite TEA	6264	4880	3901	3395	2040	1848

Figure 2: Elastic TEA (cm-g) vs. Degree of Recycling

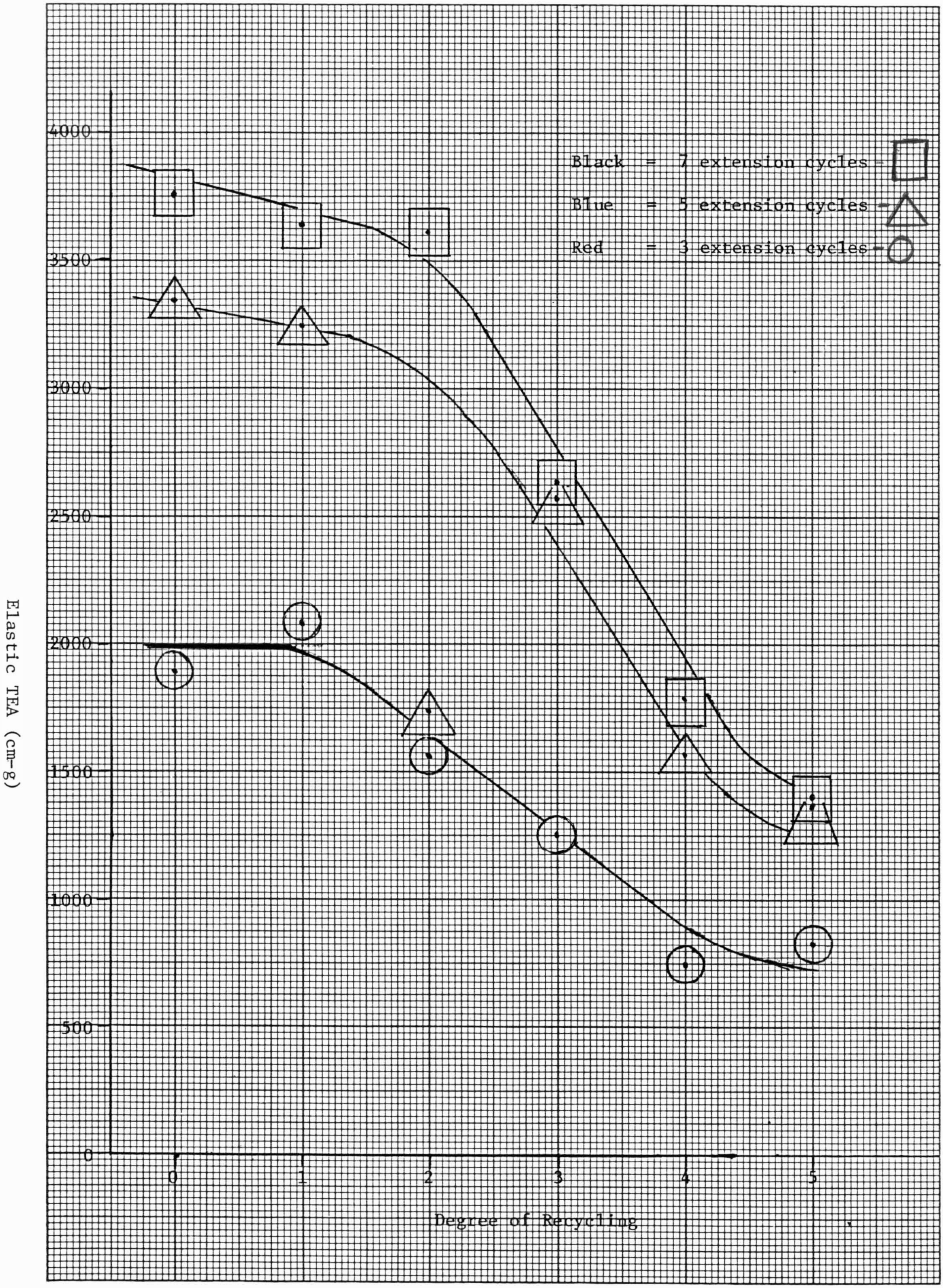


Figure 3: Plastic TEA (cm-g) vs. Degree of Recycling

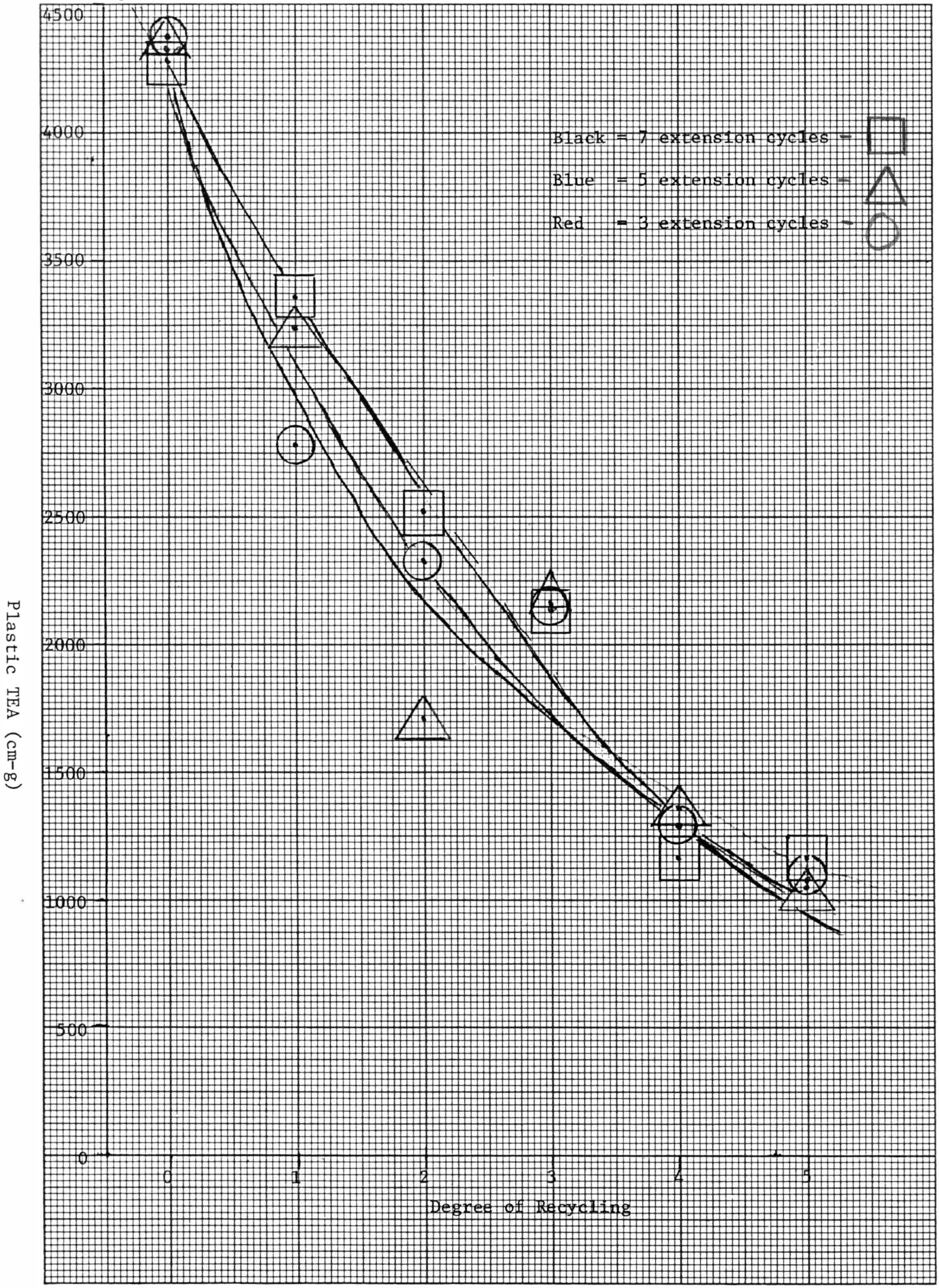
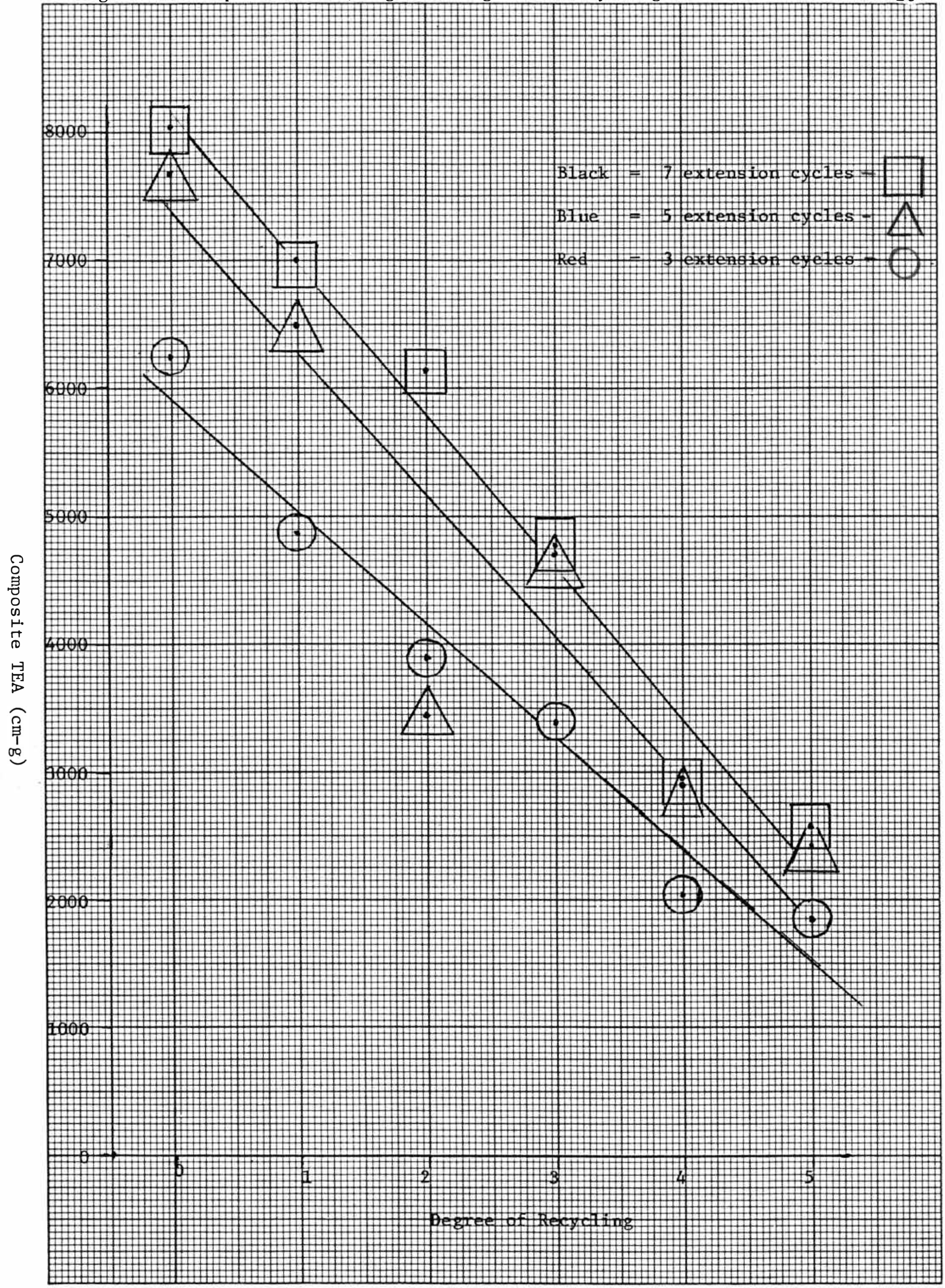


Figure 4: Composite TEA (cm-g) vs. Degree of Recycling



DISCUSSION OF RESULTS

The graphical representations of how the recycling of paper affects TEA, brings out some interesting pheonmena. It is obvious that increasing the number of extension cycles will result in an increase in TEA. This is true for elastic and plastic components of TEA. This would certainly be expected for the elastic component, since infinite TEA could be theoretically obtained by using an infinite number of extension cycles.

The plastic portion has a definite and limited amount of energy which it can dissipate. The amount of energy which the plastic portion can dissipate is affected by the dynamics of the testing procedure. If the paper is stretched a small amount in the plastic region, the fiber network will be able to accomodate and distribute that strain, in a certain amount of time. If the paper is stretched a greater amount in the plastic region, the fiber network will have to distribute more energy at a faster rate. The net effect is that the fiber network is not able to distribute the strain as well in large extensions as it is in small extensions. When the strain is not dissipated, it is localized. The localized or concentrated strain will cause the sheet to rupture at lower levels of extension or TEA. This explains why plastic TEA decreases with larger extension graduations.

Composite TEA is the sum of plastic and elastic TEA. Therefore, since both of these components decrease with increased recycling levels, the composite TEA should also decrease with recycling. This can be observed in the graphical data. The results for composite TEA are in agreement with previous studies (2).

It is interesting to note that the relationship between composite TEA and degree of recycling is essentially a linear one (for as many as five degrees of recycling). The relationship between elastic TEA and degree of recycling is certainly not linear. The relationship for plastic TEA and degree of recycling is also non-linear. It seems to be an unusual coincidence that the non-linearity of these components cancel each other out when they are added together, and form a linear relationship.

The non-linear decrease in elastic TEA cannot be easily explained. As seen in the graphs, elastic TEA is essentially unchanged after the first recycling of the paper. In two cases it is still almost unchanged after two recyclings. It is only after the first or second recycling that elastic TEA begins to decrease.

The non-linear decrease in plastic TEA is in dark contrast to the elastic TEA situation. Plastic TEA decrease sharply after the first recycle, after the third recycling the rate of decrease is diminishing.

Looking at the two contrasting relationships of plastic and elastic TEA with respect to degree of recycling, one can see that there are changes taking place in the fiber properties which effect these two types of TEA differently.

Elastic TEA is dependent on the properties and characteristics of the individual fiber. Plastic TEA is the result of fiber to fiber bonds being ruptured or fiber failure and is therefore dependent on the fiber properties which are most directly related to bonding and fiber strength.

Elastic TEA is primarily dependent on fiber rheology, thickness of the fiber wall, and the chemical composition of the fiber. Therefore small changes in these fiber properties will result in small changes in elastic TEA. On this basis,one can explain the initial stability of elastic TEA to recycling. These fiber properties do begin to change significantly after the first or second recycling and thus cause the elastic TEA to decrease.

The plastic TEA is affected immediately upon recycling, because the fiber properties which control plastic flow are changed immediately. These fiber properties are length distribution, fiber strength, and bonding ability. It has been previously demonstrated that length distribution is shifted towards smaller fibers (more fines) (3, 5). Decreases in fiber strength have also been observed in recycled paper (2, 3). Fiber strength is only important in "strong" sheets, therefore its importance diminishes as the sheet becomes weaker. The most important factor in explaining the initial rapid decrease in plastic TEA is the reduction in fiber bonding (1, 2, 3). The reduction in fiber bonding can be attributed to hardening of fibers, losses in swelling ability, and losses in flexibility.

In short although non-linear decreases in plastic and elastic TEA's are interrelated by some of the same fiber properties, there are certain fiber properties which seem to be related somewhat exclusively to either elastic TEA or plastic TEA. This concept would explain the results shown in the graphical data.

CONCLUSION

From this study it can be seen that the number of extension cycles used to rupture a sample will effect the elastic, plastic, and composite TEA's of a paper specimen. All TEA's increase as the number of extension cycles increase.

Addition of the elastic and plastic TEA's of a paper sample, results in the "canceling out" or averaging effect which is responsible for the linear relationship (linear up to five degrees of recycling) between composite TEA and degree of recycling.

Both elastic and plastic TEA decrease non-linearly as the degree of recycling increases, composite TEA decreases linearly with increased recycling (up to 5 recycles).

Knowledge of the relationship between plastic and elastic TEA and the degree of recycling, may be useful for determining whether a certain grade of paper is acceptable. If for instance a high level of elastic TEA is desired,but the plastic TEA does not need to be very high, one may wish to use virgin paper as a source of fiber.

RECOMMENDATIONS

There is a need for more knowledge about changes in fiber properties of paper which has been recycled. Studies of changes in fiber rheology, chemical composition, surface area, and flexibility would be useful for explaining the data in this experiment, and would also be useful in predicting other physical characteristics of recycled paper.

Studies similar to this one could be done utilizing different types of virgin pulp. Use of a fourdrinier type sheet former would also be of interest. Exposing the fibers to various ink removing chemicals could tell us about more important and dramatic factors which would have to be dealt with in many paper recycling mills.

LITERATURE CITED

1. Cildir, H., and Howarth, P., Paper Technol., 13, No. 5: 333-5, (Oct. 1972).

2. McKee, R.C.,; Paper Trade J., 155, (21), 34-40, (May 24, 1971).

3. Horn, R.A.; Paper Trade J., 159, No. 7/8, 78-82, (Feb. 17/24, 1975).

4. Van den Akker, J.A.; Tappi, 53 (3), 388-400, (March, 1970).

5. Szwarcsztajn, E. and Przybyszky; ABIPC #5915, Vol. 45.

6. Marton, R., Tappi, 42, 948-53, (12), (Dec. 1959).

7. Van den Akker, J.A.; Tappi, 41, 416 (1958).

8. Jayne, B.A.; Tappi, 42 (6), 461-67, (June, 1959).

9. Brezinski, J.P.; Tappi, 39 (2), 116-128, (Feb. 1956).

10. Rance, H.F.; Tappi, 39 (2), 104-115, (Feb. 1956).

11. Steenberg, B.; Pulp,Paper Mag. Can., 50 (3): 207, (1949).

12. Van den Akker, J.A.; Tappi, 53 (3), 388-400, (March, 1970).

13. Corte, H. and Kallmes, O.J., "Formation and Structure of Paper", (F. Bolem Ed.) Transactions of Symposium Held at Oxford, Sept. 1961, London, Tech. Sect. Brit. Paper and Board Makers Assoc., 1968, pp. 351-368.