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Epoxy Resins for Superconducting Magnet Encapsulation

D Evans J T Morgan G B Stapleton

Science Research Council

Chemical Technology Group
Rutherford High Energy Laboratory
Chilton Didcot Berkshire
1972

SBN 90237645 4

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EPOXY RESINS FOR SUPERCONDUCTING MAGNET ENCAPSULATION

D Evans J T Morgan G B Stapleton

ABSTRACT

Experimental work on the evaluation of epoxy resin systems for use at liquid helium temperatures is reported. The various criteria are discussed and the tests used to evaluate the potential worth of a large number of systems are described. Tabulations are given of the performance of selected resin systems.

Chemical Technology Group
Rutherford High Energy Laboratory
Chilton Didcot Berkshire

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1 INTRODUCTION

The increased interest in the use of superconducting magnets in high energy physics applications has lead to a search for electrical insulators and encapsulating materials suitable for use at very low temperatures. The need in superconducting magnets, is for an encapsulating material to give mechanical integrity to the magnet coils. This would prevent any conductor movement or energy release which might lead to frictional or other heating effects and a reversion from the superconductive to the normal state.

The ideal encapsulant for use in superconducting magnet coils would have the following properties:

a. Resistance to severe thermal shock.

b. Highly penetrating for impregnation of closely wound coils.

c. A thermal contraction which matches that of superconductors.

d. High thermal conductivity.

e. Resistance to high energy radiation.

f. Good mechanical strength and resistance to creep under clamping forces.

g. Reasonably good electrical resistance properties.

h. Can be machined easily.

A single material which possesses all of these properties is not likely to be found. A compromise of properties must therefore be sought to fulfil the demands made by a particular component and conversely, the design of superconducting apparatus must take full account of the properties of the range of encapsulating materials available at the present stage of development. This report gives information on a number of epoxy resin systems which have found use, or are potentially useful, in the construction of superconducting magnets for high energy physics application.

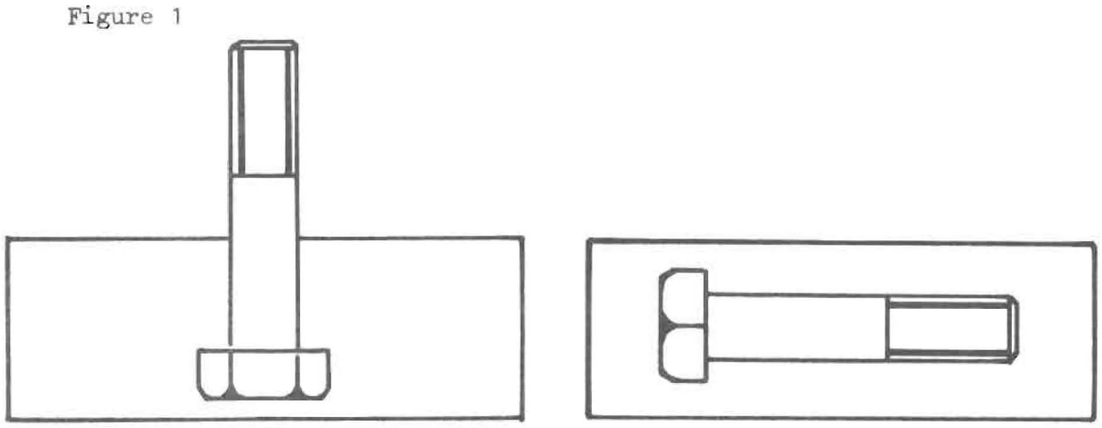
2 EXPERIMENTAL METHODS

2.1 Cooling and Shrinkage Stresses

A number of thermal shock and resin shrinkage tests have been reported but in the main these tests are of little quantitative value. Attempts have been made to find experimental methods for determining shrinkage stress but these have not yet proved to be of value.[1]

It was therefore decided to adopt a simple test specimen comprising a resin block containing an insert. The insert chosen was a brass bolt since these are readily available, are reproducible in form and have a thermal expansion coefficient similar to the copper components used in coil construction. The form of these specimens is shown in Figure 1 and consists of a resin block 2 1/2 inches diameter by 1 inch thick containing 1 3/4 x 3/8 inch BSF brass bolt. The position of the bolt in the casting is optionally located either (a) axially with the threaded end protruding or (b) suspended diametrically by glass fibre tape to be fully encapsulated.

Figure 1



(a) (b)

Tests were also conducted on pure resin blocks without inserts 2½ inches diameter, 2½ inches in height.

These specimens are plunged into liquid nitrogen, removed after several hours, allowed to warm to room temperature and examined for signs of cracking. Specimens which do not crack are recycled several times.

2.2 Impregnation Characteristics

(a) Unfilled Resin Systems

The impregnating properties of the resin mixes are determined using a novel wetting and penetration test.[2] This consists of a pyrex tube approximately ½ inch diameter and 20 inches long filled to near the top with 3000 grade Ballotini*. Resin is poured under vacuum into the top of the tube to cover the Ballotini, the tube is then removed from the vacuum and placed in an oven at the appropriate cure temperature. The depth of penetration of the resin into the Ballotini layer is given as a measure of the impregnation properties of the resin mix.

(b) Filled Resin Systems

This test is the same as for unfilled systems except that 12-14 mesh spheroidal alumina particles are used instead of Ballotini.

2.3 Contraction of Materials on Cooling to Liquid Nitrogen Temperature

The following apparatus was constructed so that integrated thermal contraction between room temperature and liquid nitrogen temperature could be readily determined. It is shown diagramatically in Figure 2 and consists of a silica tube into which the specimen is placed together with a silica rod located on top of the specimen.

Figure 2

*Glass spheres manufactured by the Ballotini Manufacturing Company Limited
Pontefract Road Barnsley Yorks

On immersing the lower end of the tube into liquid nitrogen the differential movement between the rod and tube is measured by means of a linear displacement transducer*. The use of a very slight vibration to the apparatus assists in removing any frictional effects.

2.4 Mechanical Properties of Materials at Low Temperature

Strength and modulus measurements are made at liquid helium temperatures using a specially modified Instron tester described elsewhere[3]. The results on resin systems discussed in this report are tabulated in Table 9.

MATERIALS EXAMINED

3.1 Resin Systems

Many different epoxy resin systems were tested. However, the selection was largely limited to mixes having low viscosity and relatively long 'pot lives' and therefore suitable for impregnation of closely wound coils. The complete list of resins and hardeners is given in Tables 1 and 2 but the actual mixes used are not given except for those which have been shown to have good thermal shock resistance or which illustrate the behaviour of general resin types.

Whilst it is appreciated that changes in curing schedules can modify the behaviour of the cured resins towards thermal shock, this variable is largely ignored. Various standardised curing times and temperatures are adopted to limit the size of the programme; nevertheless certain conclusions can be drawn from the limited number of results.

Variations in resin/hardener ratio also modify the behaviour of cured resin systems and from previous work in this field it is observed that resins containing rather more than the stoichiometric amount of hardener have better thermal shock resistance.[4]

*7 DCDT
Hewlett Packard Bath Road Slough Bucks

3.2 Fillers and Reinforcements

The effect of fillers on the thermal shock resistance of epoxy resins was determined by incorporating a wide range of these materials into the two basic epoxy resin formulations given below.

1		2	
	pbw		pbw
MY 740	100	MY 740	100
D 230	44	Metaphenylene diamine dissolved in N-methyl-2-pyrrolidone	14
Cure 16 hours at 60°C		Cure 3 hours at 100°C	

The complete list of fillers examined is given in Table 4. The amount of filler incorporated into each mix was such that the mix was just pourable at room temperature and therefore potentially useful for simple casting operations. Where fine particle fillers were used and dispersion was difficult a colloid mill* was used, otherwise the fillers were incorporated into the resins by hand mixing.

4 DISCUSSION OF RESULTS

The experimental results are fully tabulated at the end of the report in Tables 5 to 9.

4.1 Unfilled Resin Systems

From this programme of tests, the following general observations are made:

(a) Of the experimental methods described earlier the thermal shock test was found to be the least satisfactory, some specimens withstanding the test and other, apparently identical, specimens failing. Nevertheless, the test is of considerable value in

*Premier 84 Colloid Mill manufactured by Premier Colloid Mills Limited Hersham Trading Estate Walton-on-Thames Surrey

enabling a first selection of resin systems to be made. Not more than five specimens of each type were tested and in the completely encapsulated bolt specimen, no unfilled resin system gave five replicates that could withstand repeated plunging into liquid nitrogen, although, for several systems all five specimens were uncracked after the first immersion.

(b) The use of non-reactive flexibilisers and reactive diluents, is to be avoided in epoxy resins for use at very low temperatures; many were found to disintegrate explosively when immersed in liquid nitrogen.

(c) The resins need to be fully cured and cure temperatures as high as practicable are generally to be preferred.

(d) It was observed that epoxy resins cured with primary amine hardeners gave lower integrated thermal contractions (R.T. to 77K) than anhydride cured epoxies.[5]

(e) All of the more shock resistant resins tested in this report contain chains of polyether bonds.

(f) Resin systems that are flexible at room temperature give higher integrated contractions on cooling to low temperatures. This is considered to be due to the higher temperature coefficient known to apply to materials in the viscoelastic state.

4.2 Resin Systems Containing Particulate Fillers

It was observed that most fillers reduce the extent of cracking in resins which crack readily but offer much less improvement to the tougher resins.

The fillers found to improve the crack resistance of resins are as follows:

Chinese Talc
Zirconium Silicate
Alumina
Aluminium powder
Lead powder
Glass microballoons
Phenolic microballoons
PTFE powder

In concentrations, which give stiff flowing mixes, all of these fillers are capable of producing specimens which stand repeated liquid nitrogen immersion. The most successful filler was undoubtedly Chinese Talc which was found to give non-cracking specimens in a wide variety of formulations and at various concentrations. The microballoons, PTFE powder and talc, are of value probably because they introduce into the system some ductility at very low temperatures. The two refractory fillers probably function because they increase the thermal conductivity of the resin and reduce thermal contraction to levels comparable with or lower than the metal inserts. The two metal powders, whilst producing crack resistant specimens, increase the electrical conductivity to unacceptable levels; however in lower concentrations in combination with talc or microballoons they are essentially non-conducting and produce good thermally shock resistant materials.

The thermal contraction results for the filled mixes are given in Table 9 and variation in thermal contraction with filler loading is given for talc and zirconium silicate in Figures 3 and 4. It may be observed that several materials have integrated contractions similar to that of superconducting cables and magnet steel.

Impregnation tests were carried out on a limited number of resin systems and the results are given in Table 8. The filled mixes show very little penetration into the Ballotini system, the filler particles filtering out and arresting further flow.

5 APPLICATIONS OF EPOXY RESINS IN SUPERCONDUCTING MAGNET CONSTRUCTION

5.1 The Use of Unfilled Systems

Provided that the magnet coil is closely wound and contains no resin-rich areas, it may be successfully impregnated using a conventional anhydride cured epoxy resin such as mix 1 given in Table 5. Many successful superconducting solenoids have been manufactured using this resin system. In some cases, small resin-rich areas may be unavoidable; however, if these areas are tightly packed with glass fabric or glass flock it should prove satisfactory. A number of resin systems described in this paper have improved resistance to thermal shock and these should now be considered especially where small resin rich areas are unavoidable.

5.2 Fibrous Fillers in Epoxy Resin Systems

The incorporation of fibrous fillers has a most beneficial effect on the resistance of epoxy resins to thermal cracking. Their use however is probably limited to 'dry stuffing' with flock and/or winding with woven tapes followed by subsequent impregnation. If the packing of dry fibres into the coil structure can be achieved with complete elimination of resin-rich areas then this technique has considerable merit. The incorporation of fibrous fillers into resin mixes in amounts sufficient to prevent cracking, results in the formulation of non-flowing pastes. A possible exception to this is resin system number 117 which contains very short fibres.

5.3 Spheroidal Alumina Filler with Shock Resistant Epoxy Resins

This technique consists of vibrating sintered spheroidal alumina particles into all unfilled areas of the coil. In this connection, it may be convenient to use graded particle sizes and, for example, vibrate small particles into areas between coil windings and large spheroidal particles into the larger areas. The whole assembly is then impregnated with a thermally shock resistant resin such as those given in Table 7. A number of superconducting magnet coils have been successfully made using this technique with resin system 43H. In any particular design, the penetration of the resin into the dry

filled structure is important and may be determined using the appropriate size of aggregate in a manner analagous to the method described in section 2.2. If a low viscosity resin system is employed this technique may prove satisfactory using glass microballoons, but this possibility has not yet been fully explored.

5.4 Particulate Fillers in Epoxy Resin Systems

Particulate fillers may be selected to impart improvements in strength, thermal conductivity or to reduce thermal contraction. The use of filled resins systems in magnet coil construction is however limited by their poor penetration characteristics. Systems with desirable loadings of fillers can be made to flow into large resin-rich regions within the coil geometry but, with closely packed coils, filtration of filler invariably occurs. Systems containing fillers of very small particle size (<10μ) will in some cases flow into closely packed cables but in general these systems are not especially crack resistant.

An alternative process, which merits consideration is the use of cables or windings pre-impregnated with a flexible resin system e.g., system 97. A heavily filled mix, e.g., system 176, might then be used to encapsulate further and consolidate the windings and other components within the magnet.

5.5 Wet Lay-up Techniques

The discussion so far has considered techniques of construction involving the impregnation or encapsulation of coil assemblies with resin following complete evacuation of air. A further technique that is sometimes employed involves "trowelling" wet resin into the coil concurrently with winding. This process more readily permits coil building layer by layer with a cure after each stage. Furthermore, the technique permits the use of heavily filled resin mixes. However, wet lay-up techniques do not give the structural integrity of vacuum impregnated castings and also do not prevent the entrainment of large quantities of air within the coil lay-up.

CONCLUSIONS

A wide range of epoxy resins, hardeners and fillers in various combinations has been examined for potential use at very low temperatures. The range of materials examined is by no means exhaustive and further work on both unfilled and filled epoxy resin materials is planned. Epoxy resins have a limited amount of resistance to thermal shock and careful attention to the design of components is necessary if the resins are to perform satisfactorily at very low temperatures.

The effects of cooling rate on the behaviour of resins is considered to be significant but has not been discussed in this paper and is the subject of a separate study.

In the approach to the design of a magnet coil, consideration must first be given to the use of reinforcement by glass or other fibres in the form of flock, rovings or fabrics. Where the use of such fibrous materials is precluded, recourse should then be made to the consideration of other materials and techniques discussed in this report.

7 ACKNOWLEDGEMENTS

Acknowledgement is made to Mr G E Simmonds in whose department this work was performed, also to many members of Applied Physics Division and the Department of Engineering Science for helpful discussions on the subject.

8 REFERENCES

1. Handbook of Epoxy Resins Lee H, Neville K, McGraw Hill 1967 section 17-18.

2. Report in preparation.

3. Mechanical Testing at 4.2K Evans D, Micklewright C E, Sheldon R, Stapleton G B, - RPP/E10.

4. Technical Bulletin - Jefferson Chemical Company Inc.

5. Shimp D A. IEEE 32 C79-69.

6. Soffer L M, Molho R. Cryogenic Properties of Polymers Marcel Dekker Inc NY, P. 87.

Table 1

List of Resins

Manufacturer	Designation
Ciba-Geigy (UK) Limited Plastics Division Duxford Cambridge England	MY 740 MY 745 MY 790 MY 720 MY 750 CY 208 LY 558 X33/1189 CT 200
Shell Chemicals UK Limited Shell Centre Downstream Building London S E 1	Epikote 828 " 871 DX 221
Bakelite Xylonite Limited Plastics Materials Group 12-18 Grosvenor Gardens London S W 1	ERL 0510 ERL 4206 ERL 4201 ERLA 4617

Table 2

List of Hardeners

Manufacturer	Designation
Ciba-Geigy (UK) Limited Plastics Division Duxford Cambridge England	HY 906 HY 964 MS 2010 HY 219 HT 907 X83/319 HY 951 HY 931
Jefferson Chemical Company Inc 1121 Walker Avenue PO Box 53300 Houston Texas	Jeffamine D 230 " D 400 " D 1000 " D 2000 " T 403
Anchor Chemical Company Limited Clayton Manchester England	Anchorflex 150 " 70
Du Pont Company (UK) Limited 76 Jermyn Street London S W 1	MOCA
BASF (UK) Limited Earl Road Cheadle Hulme Cheshire	Laromin C260

Table 2 (cont.)

Manufacturer	Designation
BDH Limited Poole Dorset	m-phenylene diamine

Table 3

List of Modifiers and Diluents

Manufacturers	Designation
Du Pont Company (UK) Limited 76 Jermyn Street London S W 1	Adiprene L 100
Proctor and Gamble Limited PO Box 9 Hayes Middlesex	Flexibiliser 151
BDH Limited Pool Dorset	N-methyl pyrrolidone Polyethylene Glycol 400 " " 4000 Dibutyl phthalate
Ciba-Geigy (UK) Limited Plastics Division Duxford Cambridge	Phenyl Glycidyl Ether Butyl " "
B F Goodrich Chemical Company Cleveland Ohio	Hycar liquid rubber type MTA " " " " CTBN

Table 4

List of Fillers

Manufacturer or Supplier	Type	Approximate particle size
BDH Limited Poole Dorset	Graphite powder Talc Bentonite Kieselguhr Magnesium Oxide Zirconium Oxide Lead Powder P.T.F.E. powder Polyethylene Powder Copper Powder	 less than 50 microns - less than 40 " less than 44 " less than 50 " less than 50 " - - less than 50 microns
Ciba Geigy (UK) Limited Plastics Division Duxford Cambridge	Slate Powder Marble Flour Silica Flour Aluminium Powder Mica Flour Aerosil	up to 30 microns up to 20 " up to 30 " up to 50 " up to 30 " less than 1 "
Turners Asbestos Fibres Limited Faulkner Street Manchester	Chrysotile Asbestos Fibre	25-50 mesh 200 " less than 200 mesh
Norwegian Talc (UK) Ltd 251 Derby House Liverpool 2	Micro Talc ATI " " ITI Micro Calcite VK extra Micro Calcite VKI Microdol Extra Microdol Extra 1	up to 20 microns up to 15 microns up to 8 microns up to 20 microns up to 8 microns up to 20 microns
Plastichem Limited Windsor House Esher Surrey England	Garotalc 132 Aluminium Flake Ballotini China Clay - Icecap K	up to 12 microns 1/64" sq. x 0.00045 20-40 microns 1 micron

Table 4 (cont)

Laporte Industries Ltd Grimsby Lincs	Rutile TiO_2 Tiona VC " " Runa RG Anatase TiO_2 Tiona G	up to 12 microns approx. 2 microns approx. 2 microns
Emerson & Cumming Ltd Colville Road Acton London W 3	Glass microballoons	up to 60 microns
Bakelite Xylonite Ltd Redfern Road Tyseley Birmingham B11 2BJ	Phenolic Microballoons	up to 30 microns .25 g/cc
Imperial Chemical Ind Ltd Welwyn Garden City Herts	'Fluon' PTFE Powder Grade L 169	1-5 microns
Associated Lead Manufacturing Co Ltd Crescent House Newcastle-upon-Tyne	Zirconium Silicate Zircosil D " 5 " 1 " 200	 up to 50 microns up to 4 microns up to 2 microns up to 80 microns
Colin McNeal Limited Stoke-on-Trent England	Woolastonite P4	up to 20 microns
Chemical Trading Co Ltd 25 Berkeley Square London W 1	Milled glass fibres	$\frac{1}{8}$" long 1/32" long

Table 4 (cont)

Cabot Carbon Limited Ellesmere Pont Cheshire	Carbon black Regal 315 F Sterling SOF	 .025 microns .04 microns
British American Optical Company Limited Watford	Alumina BM 302 " BM 303½ " BM 305	5 microns 11 microns 22 microns
Dynamit-Nobel Aktiengesellscaft Korund-Venkauf 403 Ratinger Bei Dusseldorf Festersti 22	Alumina BAR 13 " BAR 18	20 microns 30 microns
Smiths Industries Limited Ceramics Division St. Peters Road Rugby Warwickshire	Spheroidal Sintered Alumina Sintox Rumbling Media	up to 5/32"

Table 5

Composition of Selected Unfilled Epoxy Resin Formulations

Formulation No.	Composition	pbw	Cure
1	MY 740 HY 906 DY 062	100 80 0.5	12 hrs @ 60°C 20 hrs @ 100°C
4A*	L100 Epikote 828 " 871 MOCA	50 35 15 27.6	5 hrs @ 140°C
43H	L 100 MY 740 Epikote 871 MOCA	50 30 25 25	5 hrs @ 140°C
53	MY 740 D 230	100 44	16 hrs @ 85°C
71	MY 740 D 400 C 260	100 57 10	16 hrs @ 85°C
79	MY 740 CY 208 D 230	60 40 35	16 hrs @ 85°C

*See ref. 6.

Table 5 (cont)

97	MY 745 D 2000 D 230	100 15 20	16 hrs @ 85°C
122	MY 740 DY 021 MPD NM2P	100 10 14 6	gel @ 40°C 3 hrs @ 100°C

Table 6

Composition of Selected Filled Epoxy Resin Formulations

Formulation No.	Composition	pbw	Filler Vol %	Cure
117	MY 745 D 230 Milled glass 1/32 " $\frac{1}{8}$	100 40 100 20	25	16 hrs @ 60°C
125	MY 745 D 230 Garotalc 132	100 44 140	29	16 hrs @ 60°C
128	MY 740 HY 906 DY 062 Garotalc 132	100 80 0.5 200	31	10 hrs @ 100°C
136	MY 745 D 400 Woolastonite P4	100 58 160	30	16 hrs @ 60°C
146	MY 740 D 230 Zircosil D	100 44 600	52	16 hrs @ 60°C
161	MY 745 D 230 Garotalc 132	100 44 100	22	16 hrs @ 60°C
163	MY 745 D 230 Garotalc 132	100 44 120	26	16 hrs @ 60°C

Table 6 (Cont)

164	MY 745 121 hardener* Centriforce BM 302 " BM 303½ " BM 305	100 18 200 60 80	47	3 hrs @ 100°C
172	MY 745 121 hardener Tiona VC	100 18 400	51	3 hrs @ 100°C
176	MY 745 121 hardener Zircosil D	100 18 550	59	3 hrs @ 100°C
179	MY 745 MOCA Zircosil 200	100 35 700	59	6 hrs @ 150°C
183	MY 745 D 230 Zircosil 5	100 44 130	20	12 hrs @ 60°C
196	MY 745 X83/319 Zircosil D	100 24 550	58	at least 24 hrs at 60°C post cure 48 hrs @ 60°C
218	MY 740 D 230 Centriforce BM 303½	100 44 150	25	16 hrs at 60°C

*121 hardener is a 70% w/w solution of m-phenylene diamine in N methyl 2 pyrrolidone.

Table 7

Thermal Cycling Tests for Unfilled Resins

Formulation Number	Specimen Type	Number of Replicates	Number of Specimens Uncracked After Each Cycle 1	2	3	4	5
1	resin block	1	0				
	upright bolt	5	0				
	encapsulated bolt	5	0				
4A	resin block	2	2	2	2	2	2
	upright bolt	5	5	5	5	4	3
	encapsulated bolt	5	2	2	2	2	1
43H	resin block	2	2	2	2	2	2
	upright bolt	3	3	3	3	2	2
	encapsulated bolt	5	5	3	2	2	1
53	resin block	2	2	2	2	2	2
	upright bolt	4	4	4	1	1	1
	encapsulated bolt	2	2	1	1	1	1
71	resin block	2	2	2	2	2	2
	upright bolt	3	3	3	3	3	3
	encapsulated bolt	5	3	3	3	3	3
79	resin block	2	2	2	2	2	2
	upright bolt	3	3	3	3	3	3
	encapsulated bolt	5	4	4			
97	resin block	2	0) small internal cracks				
	upright bolt	4	0)				
	encapsulated bolt	5	5	5	5	5	5
122	resin block	1	0				
	upright bolt	1	0				
	encapsulated bolt	1	0				

Table 8

Penetration Tests on Resin Mixes

Formulation Number	Penetration into 3000 Grade Ballotini (cms)
1	30
4A	5.2
43H	6.5
53	9.2
71	11.5
79	10.3
97	22.5
183	0.7

Formulation Number	Penetration into 12.14 mesh Spheroidal Alumina (cms)
43H	> 30
125	13.0
146	7.5
151	0.5
161	> 30
163	20.5
164	26.5
176	23.6
179	11.3
183	> 30
218	> 30

Table 9

Physical Properties of Resins

Resin Mix No.	Thermal Contraction* (RT - 77)K	Flexural Properties **			
		Strength in MN/m^2		Modulus in GN/m^2	
		RT	4.2K	RT	4.2K
1	0.011	115.8	262.9	3.92	6.08
4A	0.015	10.8	293.3	0.20	6.18
43H	0.017	9.8	260.9	0.20	6.18
53	0.009	86.3	255.1	2.94	6.47
71	0.010	90.3	257.0	2.94	6.47
79	0.011	14.7	266.8	0.39	6.47
97	0.022				
122	0.009	138.3	160.9	3.53	7.95
117	0.005	113.8	201.1	10.79	12.75
125	0.005	59.8	122.6	6.97	12.75
128	0.005	58.9	78.5	7.26	12.75
136	0.006	72.6	163.8	5.40	15.70
146	0.004	70.6	240.3	10.79	29.43
161	0.007	62.8	124.6	6.28	10.79
163	0.006	53.0	117.7	6.57	12.36
164	0.003	141.3	313.9	16.28	32.96
172	0.003	120.7	270.8	16.87	25.60
176	0.002	182.5	295.3	25.60	36.59
179	0.002	215.8	255.1	19.42	40.22
183	0.006	97.1	157.9	5.89	12.95
218	0.006	73.6	232.5	8.04	14.13

*Thermal Contraction = $\frac{L_{RT} - L_{77K}}{L_{RT}}$

**Test based on ASTM D790 - 66 but results converted to MN/m^2 using 1 kgf = 9.81N

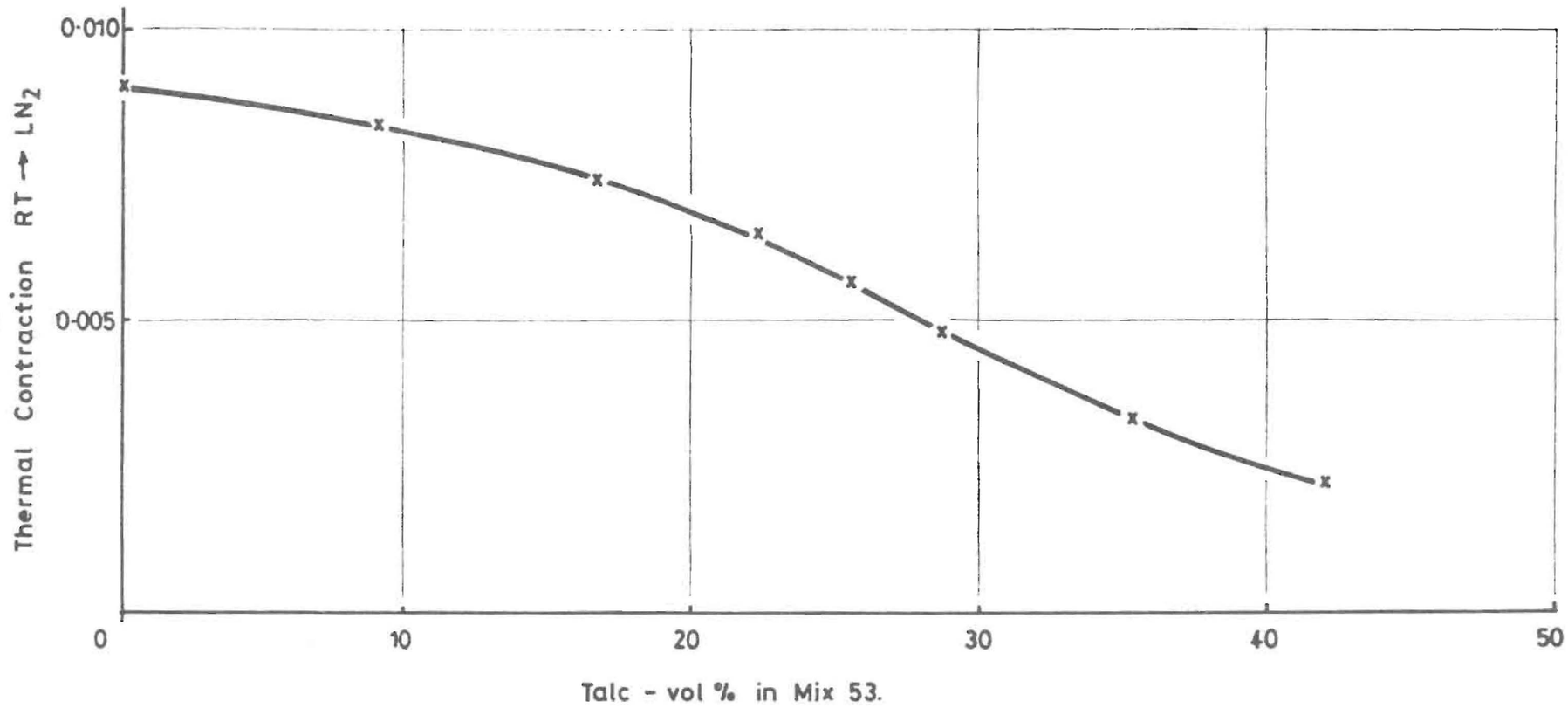


FIG. 3 THERMAL CONTRACTION V FILLER LOADING FOR CHINESE TALC.

JTM 13·12·71

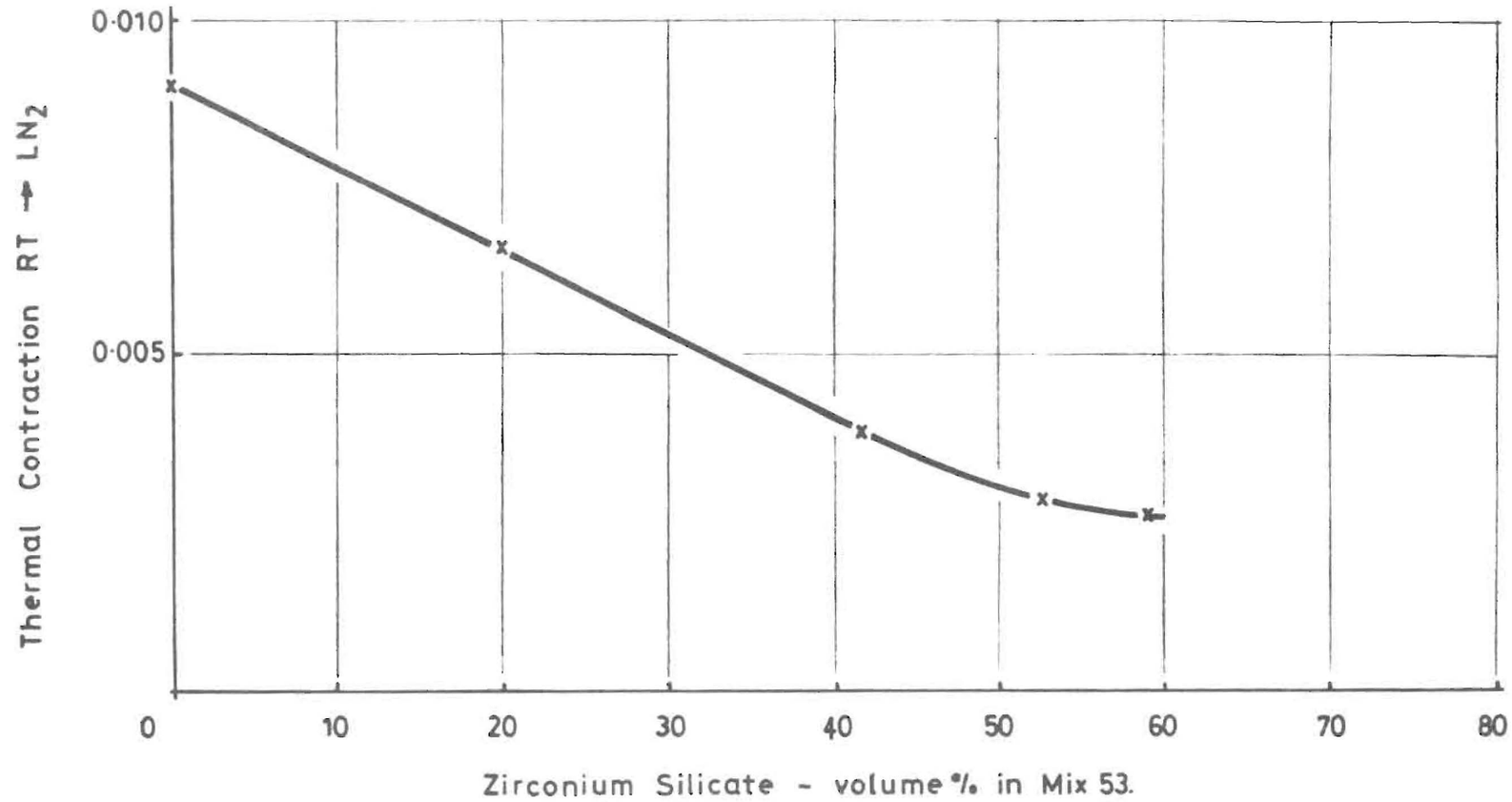


FIG. 4 THERMAL CONTRACTION V FILLER LOADING FOR ZIRCONIUM SILICATE.