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JOINT FIRE RESEARCH ORGANIZATION

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EFFECT OF TEMPERATURE ON THE CRUSHING STRENGTH OF CONCRETE

by

H. L. Malhotra

Summary

Tests have been carried out to investigate the effect of temperature on the crushing strength of concrete using 2 in. diameter by 4 in. long specimens manufactured with normal Portland cement, River sand and gravel aggregate using mix proportions by weight of 1 : 3, 1 : 4·5 and 1 : 6 and various water/cement ratios. Tests were performed at a) constant temperatures and b) constant temperature-constant stress as well as to determine the residual strength after heating. It is shown that crushing strength of concrete up to 600°C is independent of the water/cement ratio used but is influenced by the cement/aggregate ratio. Concrete specimens loaded to produce normal design compressive stress during the period of heating showed less reduction in strength than specimens without imposed load. The residual strength after heating to a given temperature in the range 200 to 450°C was approximately 20 per cent less than the corresponding strength at that temperature.

November, 1954.

File No.

Fire Research Station
Boreham Wood,
Herts.

EFFECT OF TEMPERATURE ON THE COMPRESSIVE STRENGTH OF CONCRETE

by

H. L. Malhotra

1. Introduction

Fire resistance tests under controlled conditions on concrete structures such as columns, walls, floors, beams etc. have been carried out in this country since 1935. These tests are performed in conformity with British Standard 476, the structure being exposed to heat as defined by a standard time-temperature relationship. One of the qualifying requirements is that the structure shall not collapse during the period of test and in concrete structures the strength/temperature characteristics of the concrete will determine its resistance to collapse.

In a structural member the main contribution of concrete is to resist compressive stresses. When such a structure is exposed to high temperatures failure will occur when the strength of concrete has been reduced to a value where it can no longer resist the imposed compressive stresses. The present work was undertaken to find how the compressive strength of concrete is related to its temperature, taking into consideration the variables which occur in practice.

2. Brief survey of existing knowledge

The properties of building materials at high temperatures have been investigated to some extent in the past. In the nineteen-twenties Lea and Stradling studied the resistance of materials to fire and the development of a fire resistant concrete. Some experiments were carried out on the loss of compressive strength of concrete at high temperatures (1, 2). Briefly, some tests were carried out on 4 in. concrete cubes made with normal Portland cement and heated to, and kept at various temperatures up to 700°C for periods of 2 to 3 hours, the cubes being crushed when cool enough to handle. No loss of strength was observed up to 540°C, then a rapid drop in strength, and at 650°C the observed strength showed a 40 per cent reduction.

In the second report of the work by Lea (2), experiments were carried out on $4\frac{1}{2}$ in. diameter cylinders, manufactured with Portland cement, Leighton Buzzard sand and Water Orton gravel aggregate ($\frac{1}{2}$ in. to $\frac{3}{4}$ in.). The heating and testing technique employed was identical to that mentioned above. Slight drop in strength was observed up to 300°C, followed by a more rapid reduction at higher temperatures. At 550°C only 50 per cent of the original strength was observed while at 690°C the strength retained was of the order of 20 per cent.

More recently the Japanese Building Research Institute referred to the subject in one of their publications (3). The tests were carried out on cylindrical specimens, 10 cm diameter by 20 cm long, the specimens were plunged into a muffle furnace at known temperatures, kept in the furnace for about 3 hours, then removed and crushed when cool enough to handle. The results showed 50 per cent strength reduction at 450°C and 72 per cent reduction at 600°C.

The above investigations did not deal systematically with such variables as types of aggregate, mix ratios and water/cement ratios; no tests were made while the specimens were at high temperatures; and no attention had been paid to the effect of stress on the concrete specimens during the period of heating.

3. Scope of present work

In practice many different types of concretes are in use and the selection of a particular type is controlled by factors such as strength requirements; size, shape and purpose of the structure; and availability of the aggregates. For the purposes of this investigation the type of concretes considered are those in common use as well as the type having a bearing on fire resistance problems.

In general the majority of concrete work is carried out with normal Portland cement and the locally available aggregates, of which gravel and crushed rock are the most common in this country. Crushed brick is one of the artificial aggregates which though producing concrete of lower strength than with natural aggregates has better thermal insulation properties. High alumina cement has been used instead of Portland cements when high early strength is required. The mix and water/cement ratios are governed by structural and control requirements.

The primary aim of the investigation was to determine the crushing strength of concrete at various temperatures in the hot state taking into account the mix ratio, water/cement ratio, and the types of aggregates. A number of testing conditions were imposed to simulate practical cases. As the concrete in a structure is normally in a stressed state, the effect of heating the specimen whilst under stress was to be tried. To enable an estimate of strength of a structure after it has been exposed to fire called for a knowledge of the residual strength of the concrete. Two additional aspects considered of interest were, a) structures undergoing cyclic heating and cooling; and b) structures kept at a known temperature over periods of considerable duration i.e. up to 12 months. These conditions are usually encountered in boiler and furnace foundation flues, chimneys and similar situations.

The present report covers only the first stage of the investigation and deals only with specimens made from normal Portland cement with fine and course flint gravel aggregates; the specimens included three different mix ratios and various water/cement ratios.

In the further stages of this investigation it is proposed to test concretes manufactured with other natural and artificial aggregates and also concrete made with high alumina cement. The effect of cyclic and long duration heating will also be studied.

4. Testing terminology

(a). Crushing strength of concrete heated to different temperatures and tested hot, has been referred to as "constant temperature" strength.

(b). Crushing strength of concrete heated to different temperatures and tested after it has been allowed to cool, has been referred to as "residual" strength.

(c). Crushing strength of concrete heated to different temperatures whilst under a constant compressive stress and tested hot, has been called "constant temperature constant stress" strength.

5. Experimental technique

(a) Design of the experiment. The size and shape of the specimens viz. 2 in. diameter x 4 in. long, adopted for testing were selected after giving due consideration to the method of heating, apparatus required and the time involved in carrying out the tests. The cylindrical shape was best for uniform heating and the small size section allowed a reasonably rapid rate of heating to be employed while keeping the temperature differential across the section within reasonable limits. With 2 in. diameter specimens the maximum size of aggregate was restricted to $\frac{3}{8}$ in. Two 4 in. cubes which were cast and cured along with the specimens, were tested at 28 days to denote the strength of concrete as normally measured.

In order to keep the inherent variations in the concrete and the experimental errors to a minimum, complete control was exercised over the selection of materials, the manufacture and curing of specimens, and the technique of heating and testing.

Preliminary experimental work was carried out to standardize the method of manufacture; to decide upon the number of replicates required at each temperature and the range of temperatures to be explored. The statistical analysis of the results obtained by testing two batches of twelve specimens each at normal temperature, indicated that three replicates would give for confidence limits of 0·9 a standard deviation of 10 per cent. By heating the specimens to different temperatures and crushing them it appeared that only a small reduction in strength occurred at temperatures up to 300°C. Approximately 50 per cent and 75 per cent reductions in strength were obtained at temperatures of 500 and 600°C respectively. From these tests it was decided that information of greatest use would be gained by testing the specimens in the temperature range 200 to 600°C, generally in steps of 100°C. Three replicates would be used for every variable at each temperature.

For temperature measurements a fine chromel-alumel wire thermocouple was located at the centre point of each specimen.

(b) Materials. The Building Research Station supplied the materials necessary for this investigation from their controlled and graded stocks. A brief description of the materials used is as follows:

1. Cement: normal Portland cement from a batch in which a large number of bags had been mixed in a mechanical mixer to give a uniform blend.

2. Fine aggregate: River Sand; washed and uncrushed; angular grains; maximum size 3/16 in.

3. Coarse aggregate: River Gravel; washed and uncrushed, irregular shape; size $\frac{3}{8}$ to 3/16 in.

The aggregates used were in a dry state and were kept in steel bins in a store at an average temperature of 65°F. Equal quantities of coarse and fine aggregates were found to give the grading curve shown in Figure 1.

(c) Casting and curing

The recommendations in Part 6 of B.S. 1881: 1952 were followed for preparing the concrete mix. The materials were proportioned by weight and a pan type mixer of $1\frac{1}{2}$ cu.ft. capacity used for mixing. The pan was loaded in the following order:- half the quantity of coarse aggregate; then fine aggregate; then cement and finally the remaining half of coarse aggregate. The water was added immediately before the rotation of the drum, and the usual period of mixing was 2 minutes.

Twelve steel moulds each having a 26 G. chromel/alumel thermocouple held in position at the centre point by means of a 0·010 steel wire, and two 4 in. cube moulds were fixed on a 2 ft. square vibrating table operating at a fixed frequency and amplitude. The correct vibrating time for each mix was obtained by trial to give the best compaction. The moulds were gradually filled, vibrating the whole time, to $\frac{1}{8}$ in. of the top and were capped a few hours after casting with a cement: lime: sand mortar to obtain a smoother top surface.

The specimens were demoulded 24 hours after casting and marked with their identification numbers. The first eight batches of specimens were stored directly after demoulding in a control room whose temperature was maintained at an average of 75°F and at a relative humidity of 55-60 per cent. The specimens for the rest of the investigation immediately after demoulding were submerged under water for 7 days and then transferred to the conditioning room until required for testing. This modification in the curing technique produced stronger concretes at the same age.

The 4 in. cubes were cured with the specimens and were generally tested at an age of 28 days.

(d) Heating and testing

All the crushing tests were carried out on a testing machine made for the purpose at the Fire Research Station and shown in Figures 2, 3 and 4.

The specimens were heated in an electric furnace having a 3 in. diameter x 9 in. long steel sheathed refractory tube in an insulated casing and mounted in the testing machine. Two hollow heat-resisting steel units which held the specimens in position in the furnace, transferred the load to the specimen enabling the crushing load to be applied in the hot state. Asbestos millboard pads were interposed between the faces of the specimen and the steel units to act as insulators as well as to provide a cushion for slight surface irregularities of the concrete specimen.

The load was applied by means of a hydraulic jack connected to an oil pump and was measured by a dial gauge indicator mounted on a 20 ton steel proving ring interposed between the specimen and the jack.

For the constant temperature tests the specimen was heated to the required temperature, the furnace swung into testing position above the proving ring and the specimen crushed. The furnace was cooled down to a temperature of less than 100°C by means of an air blast before inserting the next specimen.

For the constant temperature-constant stress tests, the furnace with the specimen in position was placed in the testing position and the load applied to produce the necessary constant stress prior to the start of the heating. The imposed load was kept constant during the heating period and when the specimen had attained the required temperature the load was increased until the specimen failed.

The specimens for the residual strength tests were heated in a separate furnace of similar dimensions. The specimens were kept at the test temperature for one hour and then allowed to cool down gradually to the normal temperature.

(e) Temperature control

The temperature at the centre of the specimen was measured by a thermocouple incorporated in the specimen during manufacture. A similar thermocouple positioned at mid-height in the tabular furnace indicated the furnace temperature.

While heating a temperature-differential existed between the surface and the centre of the specimen. In order to avoid causing undue damage to the specimen by an excessive value of this temperature difference during the period of heating, the rate of heating was controlled so that the two temperatures never differed by more than 100°C.

It was observed in the preliminary tests that it took 1 to 2 hours for the centre of the specimen to gain the last 20°C temperature rise and attain the same temperature as the furnace. By allowing a maximum difference of 20°C to exist between the centre and the outside of the specimen at the time of testing, the heating period was reduced to reasonable limits. The mean of the two temperatures was taken as the average temperature of the specimen.

In the beginning the furnace temperature was controlled by manual operation of a voltage regulator. Later an electronic controller was devised at the Fire Research Station which automatically exercised the approximations mentioned above. The controller, shown beside the testing machine in Figure 2, gave an audible warning when the specimen was ready for testing.

A continuous record of temperatures was kept. The average rate of heating was approximately 350°C per hour.

6. Test results

(a) General

Groups of two to five batches, each batch consisting of twelve specimens, were manufactured for each type of concrete to provide specimens for different testing conditions. Three specimens from each batch, selected at random, were crushed without heating and the mean compressive strength taken as the normal strength for the batch. Similarly three replicates at each temperature level, for each test condition, were tested. The results of the tests have been expressed as percentages of the normal strength and plotted against the temperature. Smooth mean curves have been drawn through the points.

In Table 1 are given the general manufacturing details for each batch together with the cube strength, age at testing and the test conditions.

(b) Concrete mix 1 : 3 and three water/cement ratios (groups 1, 2 & 3)

Concrete specimens of 1 : 3 mix ratio and having water/cement ratios of 0·50, 0·45 and 0·40 respectively were tested under constant temperature conditions to discover the influence of water/cement ratio. These specimens, which were placed in the conditioning room directly after demoulding were tested at ages varying from $6\frac{1}{2}$ to 10 weeks.

The results of these tests are plotted in Figures 5, 6 and 7, and in Figure 8 the three curves are shown together. The results show that the variation between the three curves is less than that experienced among the replicates of the same batch of the concrete. Although concretes of different normal strengths were produced by varying the water/cement ratio, the proportional reduction of the strength of concrete up to temperatures of 600°C appears to be independent of the water/cement ratio used.

(c) Concrete mix 1 : 3 and water/cement ratio 0·40 (group 4)

Three batches of 1 : 3 mix concrete having a water/cement ratio of 0·40 were tested at constant temperature as well as for residual strength after heating. These, and all later specimens, were immersed in water for seven days after demoulding and then cured in the conditioning room. These specimens were approximately 25 per cent stronger than the previous batches of the same mix and water/cement ratio.

The specimens for residual strength were tested 24 hours after they had cooled. The results of the tests which are plotted in Figure 9, show that residual strength is lower than the constant temperature strength. The difference of 7 per cent at 200°C, increased to 20 per cent at 450°C and decreased to 4 per cent at 600°C.

(d) Concrete mix 1 : 4·5 and two water/cement ratios (groups 5 & 6)

These specimens were manufactured from concrete using 1 : 4·5 mix ratio and water/cement ratios of 0·50 and 0·45 respectively. In addition to constant temperature and residual strength tests, a third of the specimens were tested under constant temperature-constant stress conditions. The constant stress on the specimens during the period of heating was 1040 lb. in.$^{-2}$ being the recommended value by B.S. Code of Practice, CP114 (1948), for direct compressive stress for this type of concrete. When the specimens had attained the testing temperature, the load was increased until failure occurred.

The residual strength specimens were tested two weeks after cooling to allow for any subsequent deterioration or recovery in the strength. This was adopted as a standard practice for all further residual strength tests.

The results of the tests show (Figures 10 and 11) that if the concrete specimen is under stress during the period of heating, the reduction in strength at any given temperature in the range covered by the tests is less than under no stress conditions. The difference of 4 per cent at 200°C increased to nearly 20 per cent at 500°C. Another noteworthy point is that up to the temperature of 450°C the residual strength was approximately 20 per cent less than constant temperature strength. It appears that structural and chemical deterioration may continue for periods longer than 24 hours after heating.

The mean curves for these two groups are plotted in Figure 12, and as expected show little effect of water/cement ratio in constant temperature tests.

(e) Concrete mix 1 : 6, water/cement ratio 0·65 (group 7)

The tests were carried out on specimens of concrete having a mix ratio of 1 : 6 and water/cement ratio of 0·65. A stress of 836 lb. in.$^{-2}$ was used in constant temperature-constant stress tests. The results of the test which are plotted in Figure 13, give curves similar to that for 1 : 4·5 mix concrete specimens.

(f) Other observations

Colour changes in heated concrete were observed as reported by other investigators (4). In the case of residual strength specimens the change of colour to pink started at 250°C and increased in intensity at higher temperatures. By careful observation it was possible to distinguish between the specimens having temperature differences of about 100°C. With the specimens tested hot it was noticed that the full colour change corresponding to the test temperature had not occurred when the remains of the specimen were removed from the furnace. The process of colour change continued and the specimens acquired the required intensity as they cooled. The process of hydration of iron oxide compounds (responsible for the colour change) probably required a certain time for completion and continued after the specimens had been removed from the furnace.

The formation of surface hair cracks was noticed to start at temperatures of approximately 300°C, the cracks generally tending to be horizontal. At 500°C, the specimens developed deep cracks, which increased considerably on cooling. Some of the specimens heated to about 550°C could be broken by hand on cooling.

7. Discussion of results

(a) General remarks

Concrete unlike metals is not a completely homogeneous material, Structurally it may be assumed that the particles of coarse aggregate are held together in a cement-sand mortar matrix. Even when manufactured under strict laboratory control, because of its very structure, a certain amount of variation in the test results is to be expected. From the results of the tests carried out the average variation experienced was of the order of 10 per cent, the variation in any temperature range was directly proportional to the rate of reduction of the strength in that temperature range. All the same, the mean curves draw for the different tests should provide a reliable guide when evaluating the fire resistance of concret structures.

The chemical reactions that take place when concrete is manufactured, are beyond the scope of this investigation but it will be necessary to refer to them in a general way. Briefly, the hydration of Portland cement takes place when mixed with water, the chief products of hydration being calcium hydrate. The amount of water used normally in mixing concrete is more than necessary for chemical reaction, the excess water usually disperses itself in fine capillaries in the mass of concrete. Certain chemical and physical changes take place when a piece of concrete is heated.

The uncombined moisture would evaporate and disappear at temperatures in excess of 100°C, the dehydration of calcium hydrate would occur when temperature exceeds 400°C. The crystalline transformation of quartz particles in the aggregate takes place at about 575°C accompanied by large expansion. The formation of cracks in the mortar starts in the lower range of temperatures and in the aggregate at comparatively high temperatures. The loss in the strength of mortar is approximately proportional to the rise in temperature (4). For the temperature range explored in the present investigation the main factors affecting the crushing strength are; loss in the strength of mortar, formation of cracks and the dehydration of calcium hydrate.

(b) Effect of water/cement ratio

The quantity of water used in manufacturing concrete influences the final strength after curing, the smaller the proportional amount of water used the stronger the concrete. Cement requires about 20-25 per cent of its weight of water for complete hydration. In practice a larger quantity of water is used to get the necessary workability of concrete. The surplus water stays in the fresh concrete in the fine capillaries. After curing the quantity of free or uncombined water is equivalent to the amount the concrete can retain under the prevailing conditions of relative humidity and temperature.

The test results (Figures 8 and 12) show that the proportional strength reduction in concrete specimens when heated to temperatures up to 600°C is independent of the water/cement ratio used in the manufacture of the concrete. After the evaporation of free water, obviously, it has no further effect at higher temperatures.

(c) Effect of age of specimens

Age-strength relationship of concrete has been investigated in the past and considerable information is available on the subject. In the case of normal Portland cement concrete if the strength at the age of one year is assumed to be 100, the respective strength values at the ages of 28 days and 90 days are approximately 70 and 90. Thus at ages exceeding three months there is comparatively small gain in strength.

Although no specific tests were carried out to explore the effect of age, some deduction can be made from the study of the test results. The specimens in groups 5 and 6, of the same mix of concrete, were tested at the average ages of 15 and 29 weeks respectively. The difference in the ages of the specimens appears to have had no influence on the test results. It can therefore be assumed that if the specimens are tested at ages of three months or more there would be no significant effect due to age on the test results.

(d) Effect of mix ratio

In Figure 14 mean curves of the constant temperature tests on the specimens of the three concrete mixes tried viz: 1 : 3, 1 : 4·5 and 1 : 6 are drawn. For each mix the reduction in strength at 200°C is small, and at 300°C it is of the order of 10 to 15 per cent. The rate of reduction in strength appears to increase to a maximum as the temperature exceed 400°C when the dehydration of calcium hydrate may be taking place. Fifty per cent reduction in strength occurs at 450°C for mixes 1 : 3 and 1 : 4·5 and at 510°C for mix 1 : 6.

From Figure 15, which shows the constant temperature-constant stress results for mixes 1 : 4·5 and 1 : 6, it again appears that the proportional reduction in strength is less for the leaner mix at the same temperatures.

Regarding the residual strength curves which are drawn in Figure 16, it should be mentioned again that the 1 : 3 mix specimens were tested 24 hours after cooling, whereas the 1 : 4.5 and 1 : 6 specimens were tested after a lapse of two weeks. Possibly the greater lapse of time between heating and testing in the lower temperature range in the case of 1 : 4·5 and 1 : 6 mix may have increased the amount of deterioration. The results for 1 : 4·5 and 1 : 6 mix although close together, illustrate the smaller reduction in strength for the leaner mix. For these two mixes the residual strength is approximately 20 per cent less than the constant temperature results in the temperature range of 200 to 450°C.

On the whole it appears that the smaller the mass of cement or cement mortar in a concrete, the smaller the proportional reduction at different temperatures.

(e) Effect of testing conditions

In Figure 17 are drawn the curves for the three different testing conditions imposed upon the specimens for the mixes 1 : 4·5 and 1 : 6. In each case the testing conditions have a significant effect upon the test results.

The specimens which are under a constant stress during the period of heating exhibit smaller reduction in strength than the specimens under no stress, the difference of about 4 per cent at 200°C increased to 21 per cent at 500°C. As a tentative explanation it is suggested that imposition of a compressive stress would retard the development of the cracks in the specimen, which under a condition of no stress would be free to extend.

If the temperature range is increased the two curves (i.e. constant temperature and the constant temperature-constant stress) would meet at a point where constant temperature strength is approximately of the same order as the constant stress imposed on the specimen. The specimen under stress would probably fail at a higher temperature than expected as the stress would retard the development of cracks.

The residual strength results on the other hand show that compared with constant temperature tests there is a further loss of strength during the period of cooling. In the temperature range 200 to 450°C, the residual strength appears to be approximately 20 per cent lower than the constant temperature strength. It may again be that there is an increase of structural damage i.e. due to cracks etc. when a specimen cools down from high temperatures.

Conclusions

The following conclusions can be drawn from the test results on the specimens manufactured from the t pes of concretes described in this report and in the temperature range explored:-

1. The effect of temperature on the crushing strength of concrete is independent of the water/cement ratios normally used in its manufacture.

2. The cement aggregate ratio has a significant effect on the strength of concrete exposed to high temperature. In general, the proportional reduction is smaller for leaner mixes than for richer mixes.

3. Concrete under a compressive stress of the order of its design stress has a smaller proportional decrease in strength than if the stress were absent. At certain temperatures higher than 600°C the failure would be expected to occur at the same point in both the above cases.

4. The residual strength of concrete heated to given temperatures is less than its hot strength, the difference being approximately 20 per cent in the temperature range 200 to 450°C for 1 : 4·5 and 1 : 6 mix concretes.

9. Acknowledgment

The author is greatly indebted to Mr. L. A. Ashton for his guidance during the investigation and Mr. J. H. McGuire for the design and manufacture of the temperature controller.

10. References

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TABLE I

SUMMARY OF TESTS

Group No.	Batch No.	Concrete mix	Water/cement ratio	Vibration time (min)	Curing conditions	Cube strength (mean of 2 tests) lb in^{-2} *	Specimen age at test (weeks)	Test conditions
1	1 2 3	1 : 3	0·50	13	Control room 24 hr. after casting.	3660 (6w) 4000 (8w) 3575 (10w)	6 8 10	a. Constant temperature - no stress.
2	1 2 3	1 : 3	0·45	15	do	- - -	$6\frac{1}{2}$ 7 10	a Constant temperature - no stress
3	1 * 2	1 : 3	0·40	20	do	6570 (8w) 7005 ($8\frac{1}{2}$w)	8 $8\frac{1}{2}$	a. Constant temperature - no stress
4	1 2 3	1 : 3	0.40	20	Submerged under water for 7 days, then in control room	7700 (31d) 7900 (28d) 8555 (45d)	$12\frac{1}{2}$ 13 14	a. Constant temperature - no stress b. residual strength
5	1 2 3 4 5	1 : 4·5	0·50	15	do	4187 (35d) 5790 (33d) 5920 (28d) 5740 (33d) 5810 (28d)	$29\frac{1}{2}$ $29\frac{1}{2}$ $28\frac{1}{2}$ $28\frac{1}{2}$ 28	a. Constant temperature - no stress b. residual strength c. Constant temperature-constant stress
6	1 2 3 4	1 : 4·5	0·45	20	do	6720 (28d) 6850 (28d) 6720 (28d) 6860 (28d)	15 15 15 16	a. Constant temperature - no stress b. residual strength c. Constant temperature-constant stress
7	1 2 3 4 5	1 : 6	0·65	12	do	3690 (28d) 3730 (28d) 4475 (33d) 4470 (28d) 4225 (30d)	31 30 28 $27\frac{1}{2}$ 27	a. Constant temperature - no stress b. residual strength c. Constant temperature-constant stress

* "w" stands for weeks and "d" stands for days

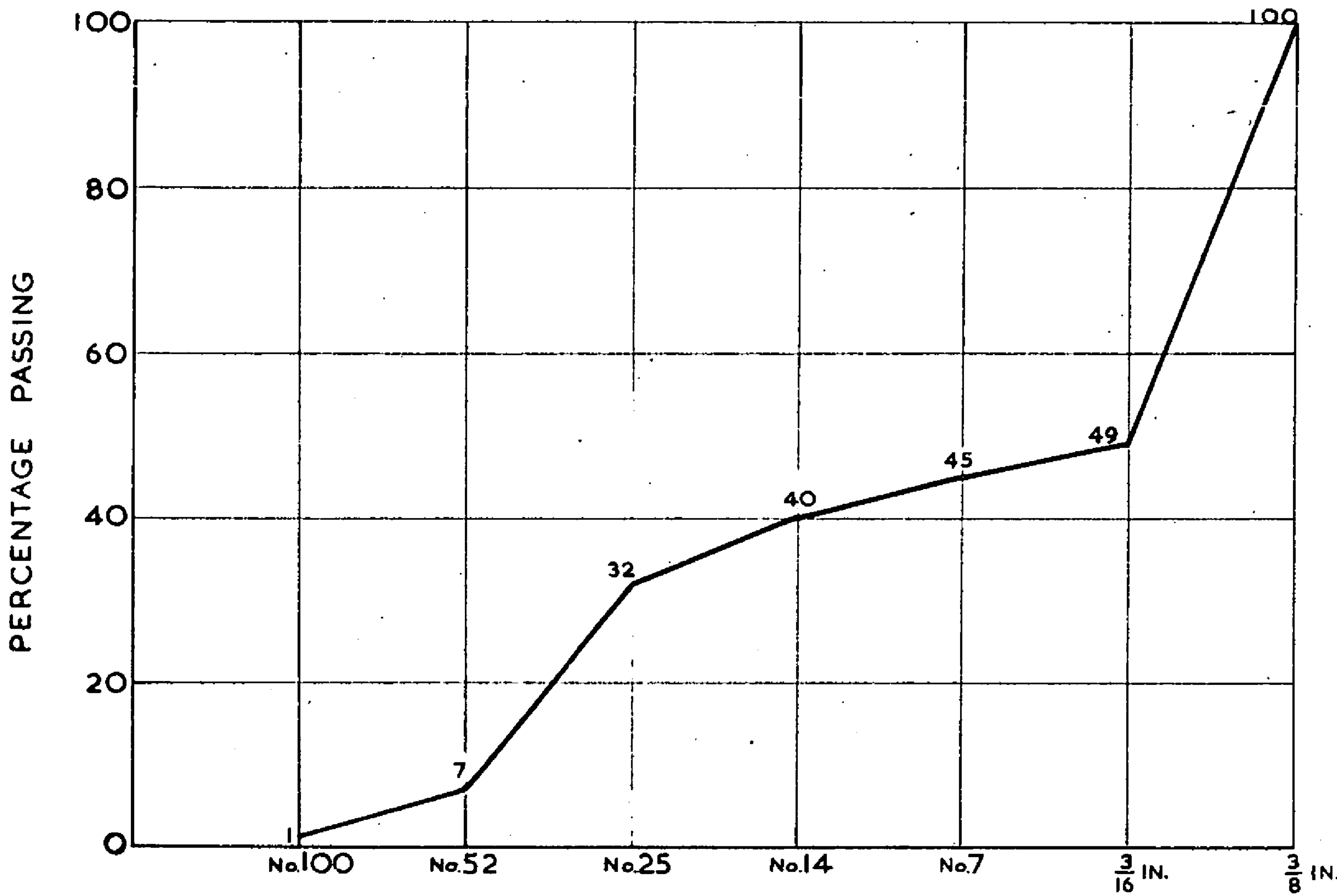

FIG. I. GRADING CURVE FOR $\frac{3}{8}$ IN. AGGREGATE

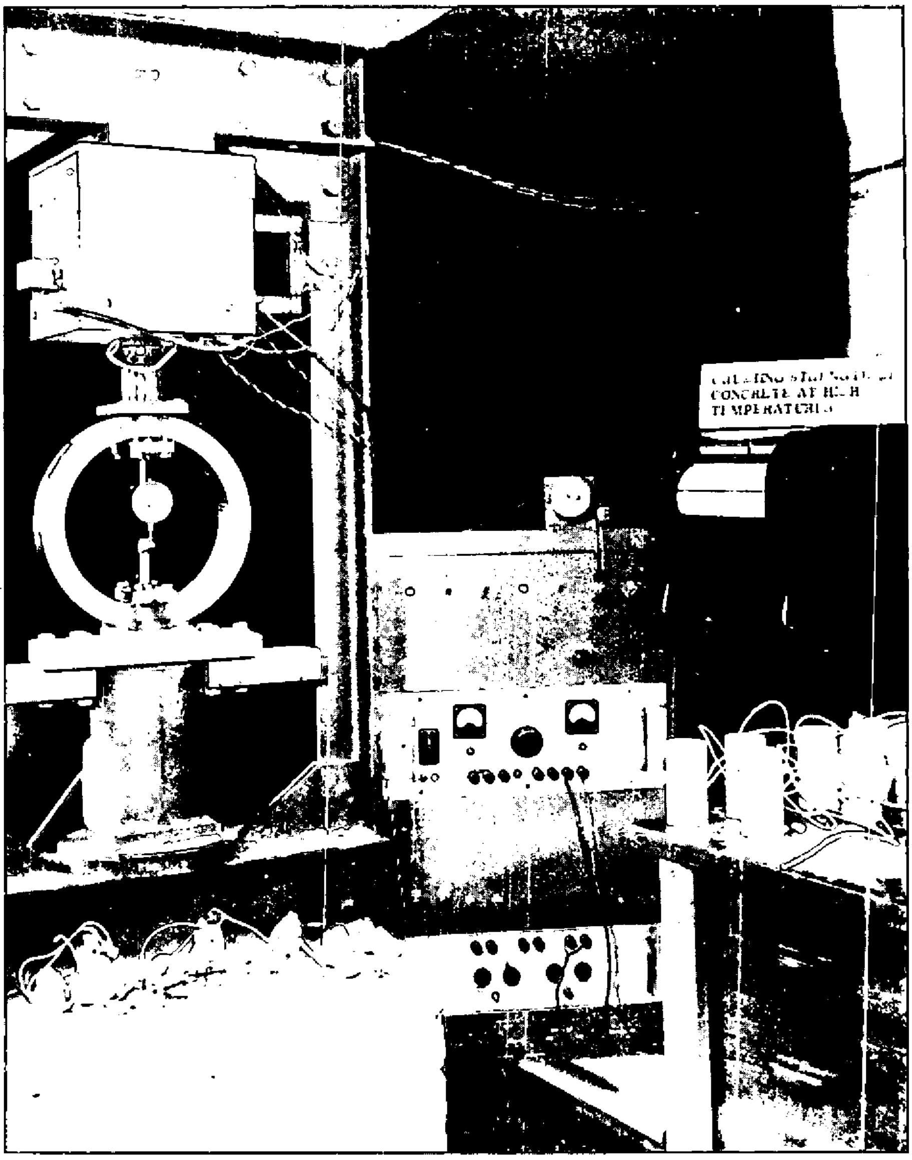

FIG.2. TESTING APPARATUS WITH TEMPERATURE CONTROLLER

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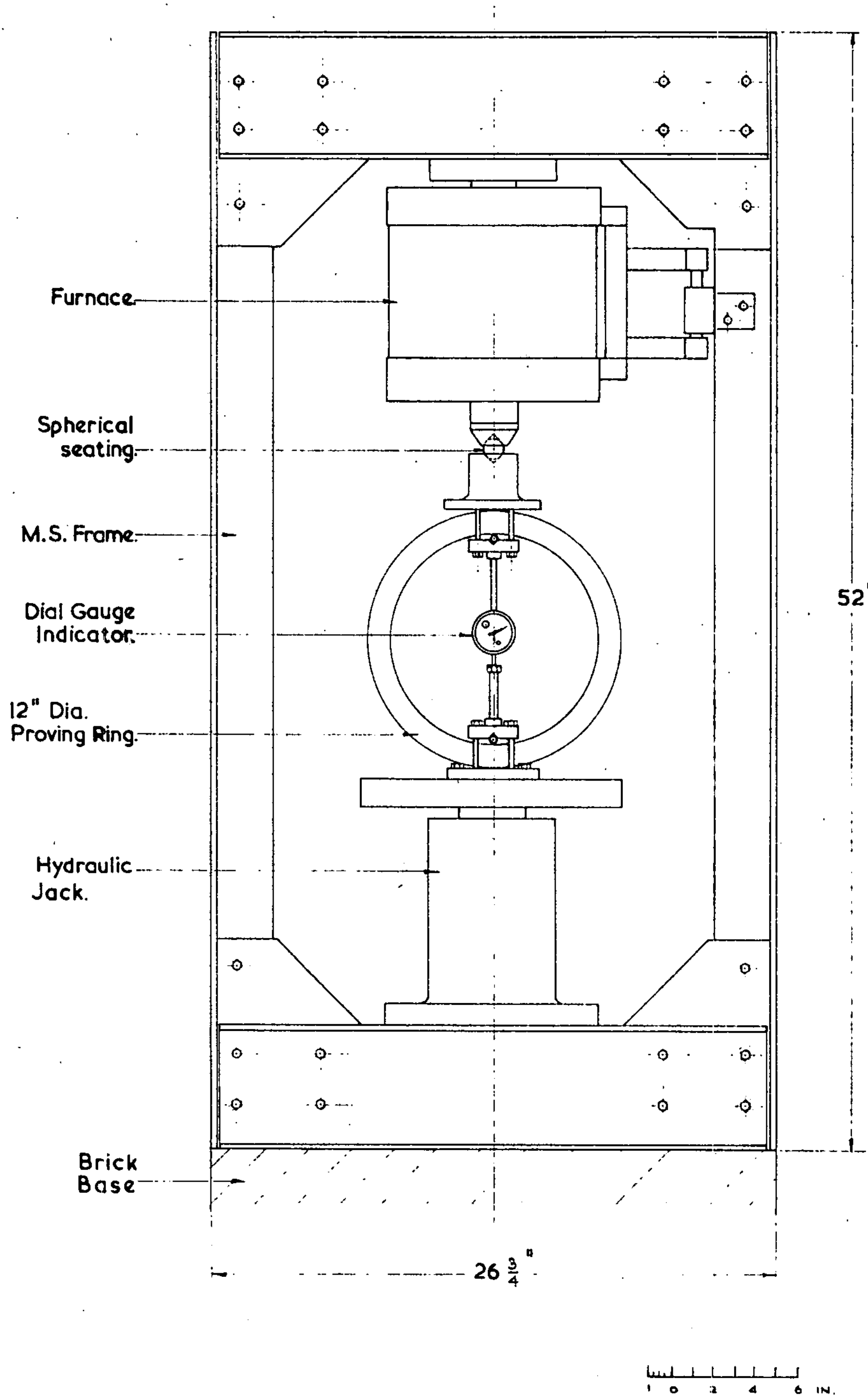
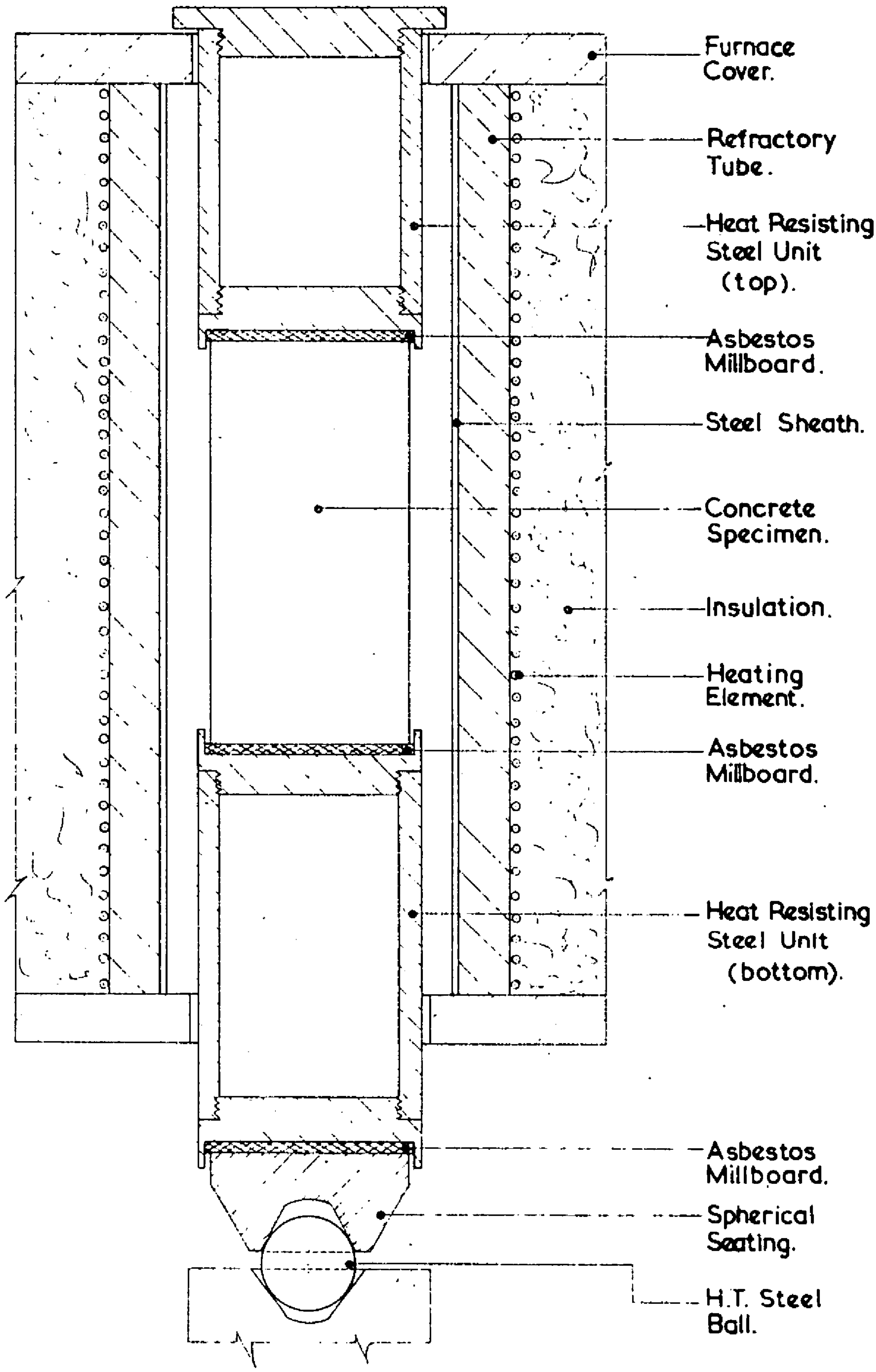


FIG. 3. TESTING MACHINE.



SECTION THROUGH FURNACE.

FIG. 4. DETAIL SHOWING TECHNIQUE FOR TESTING SPECIMENS HOT.

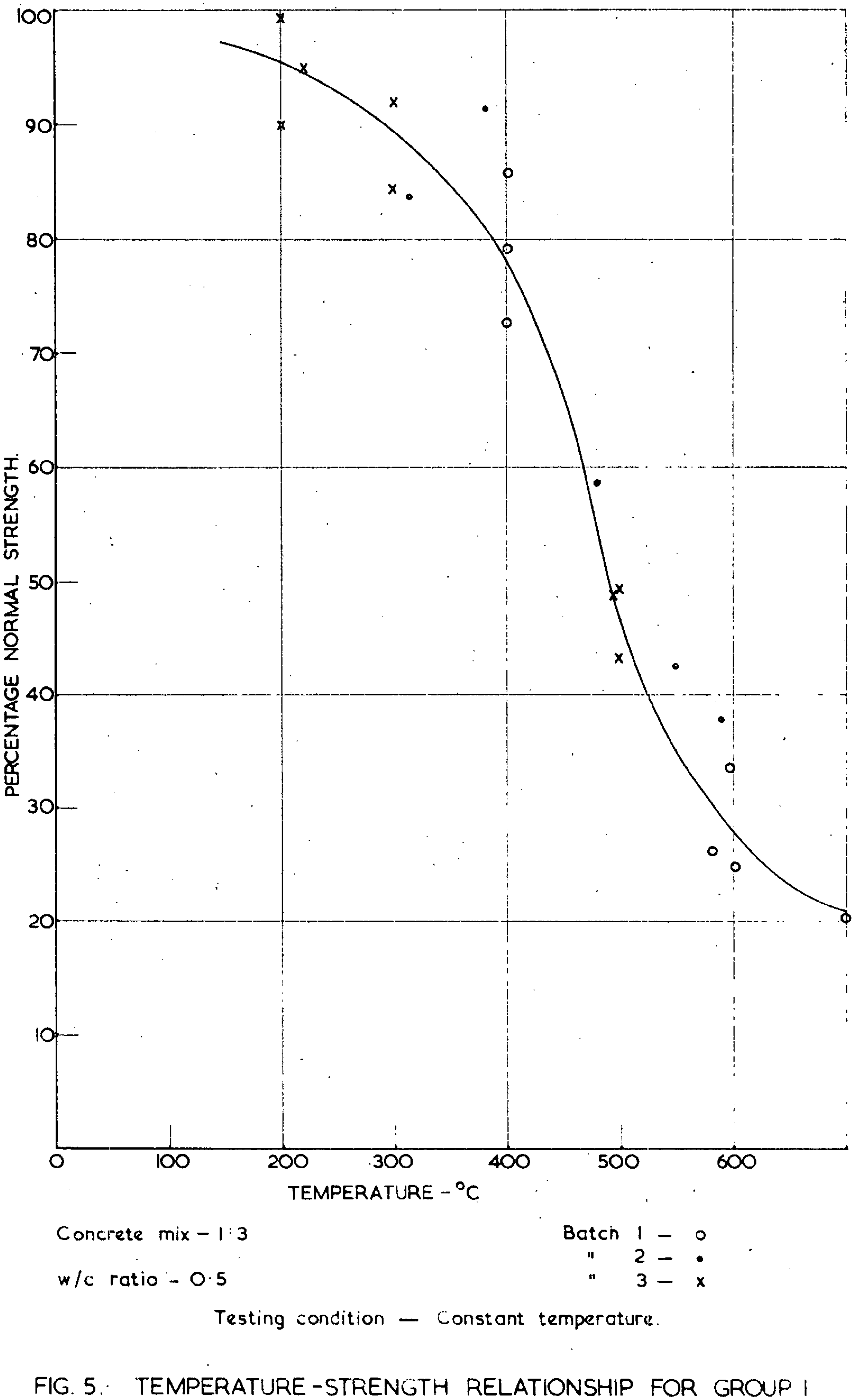
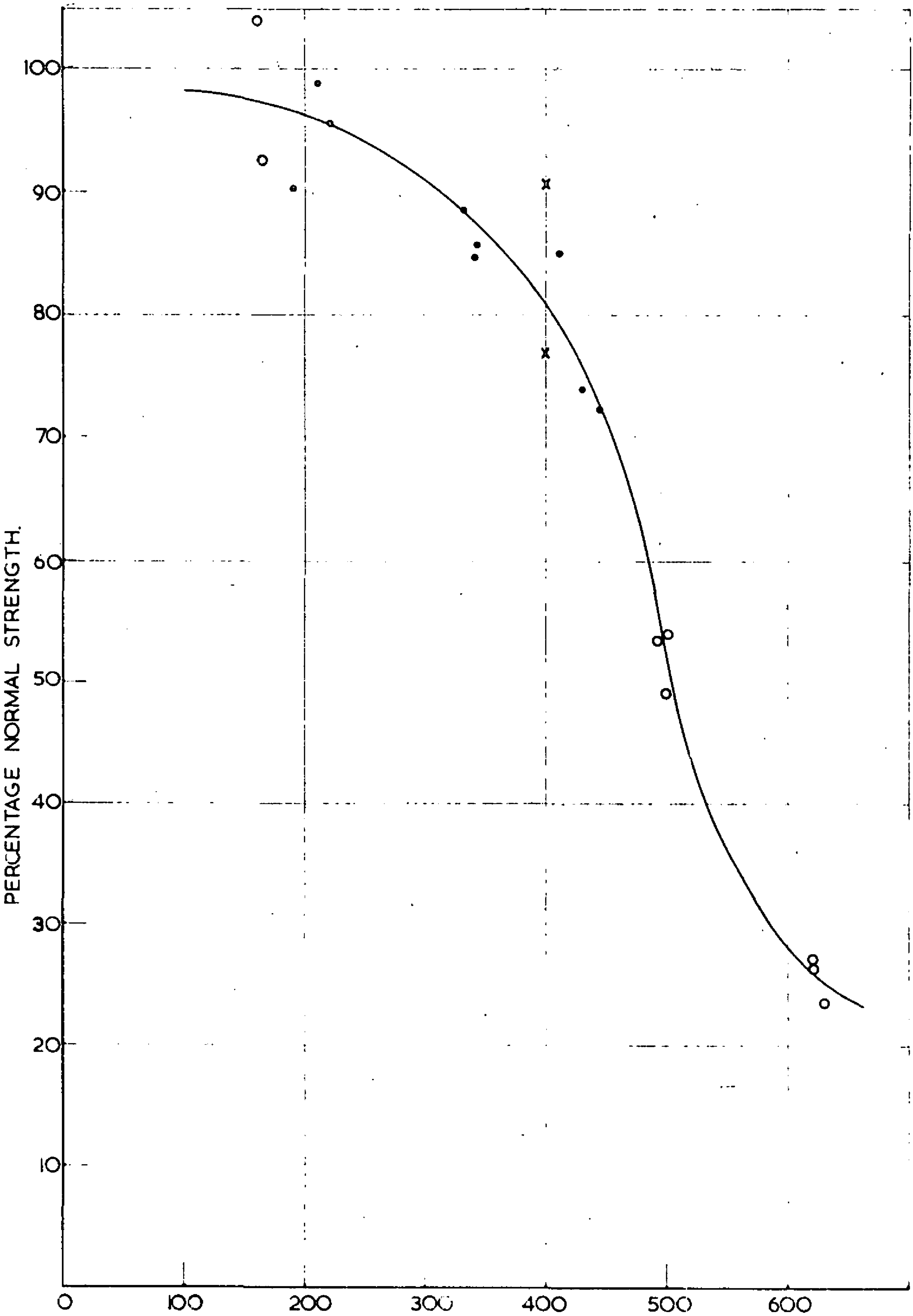


FIG. 5. TEMPERATURE-STRENGTH RELATIONSHIP FOR GROUP I SPECIMENS.



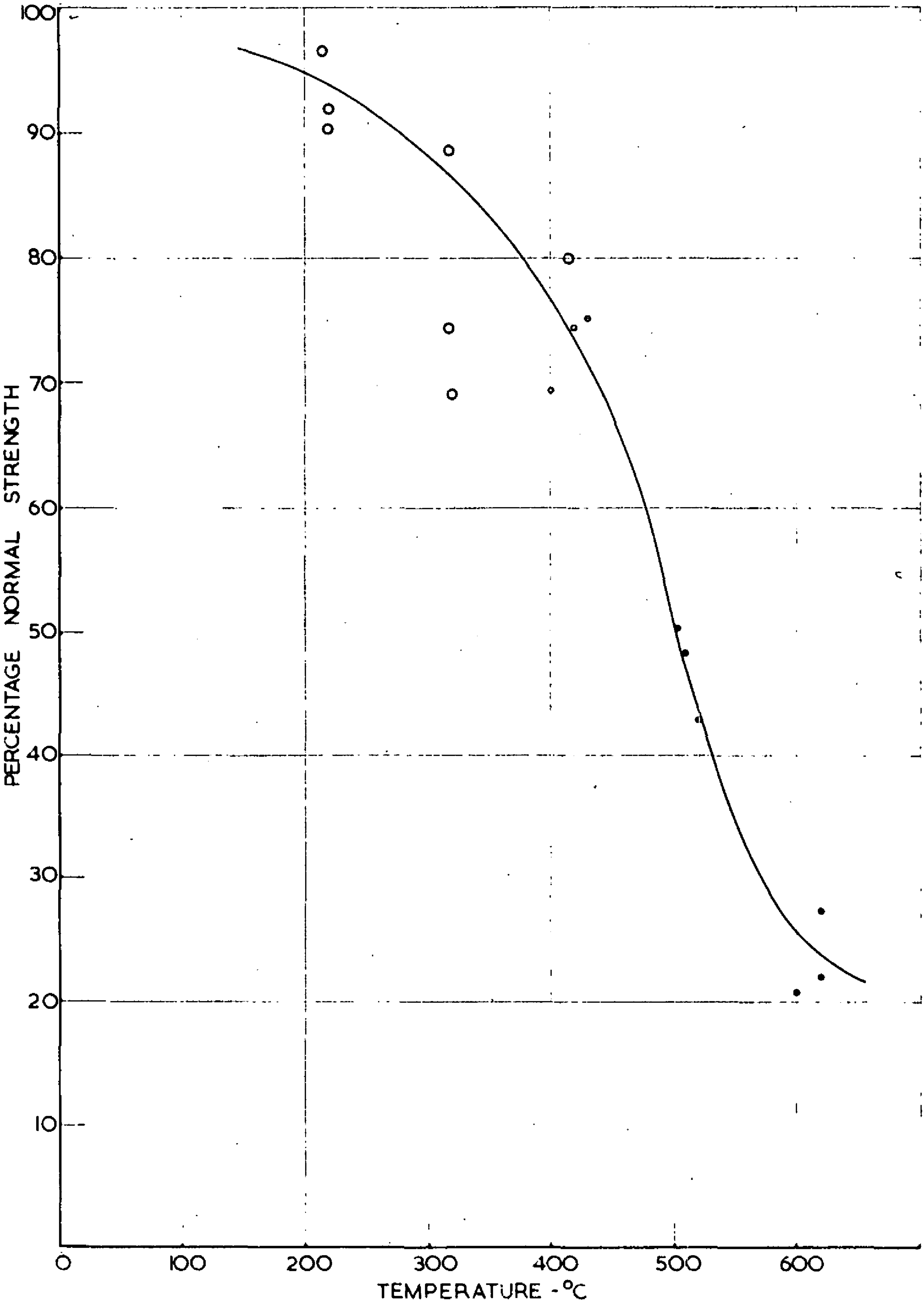
Concrete mix — 1 : 3

w/c ratio — 0·45

Batch 1 — o
" 2 — •
" 3 — x

Testing condition — Constant temperature.

FIG. 6. TEMPERATURE-STRENGTH RELATIONSHIP FOR GROUP 2. SPECIMENS.



Concrete mix – 1:3 Batch 1 – o

w/c ratio – 0·40 " 2 – •

Testing condition – Constant temperature.

FIG. 7. TEMPERATURE - STRENGTH RELATIONSHIP FOR GROUP 3. SPECIMENS.

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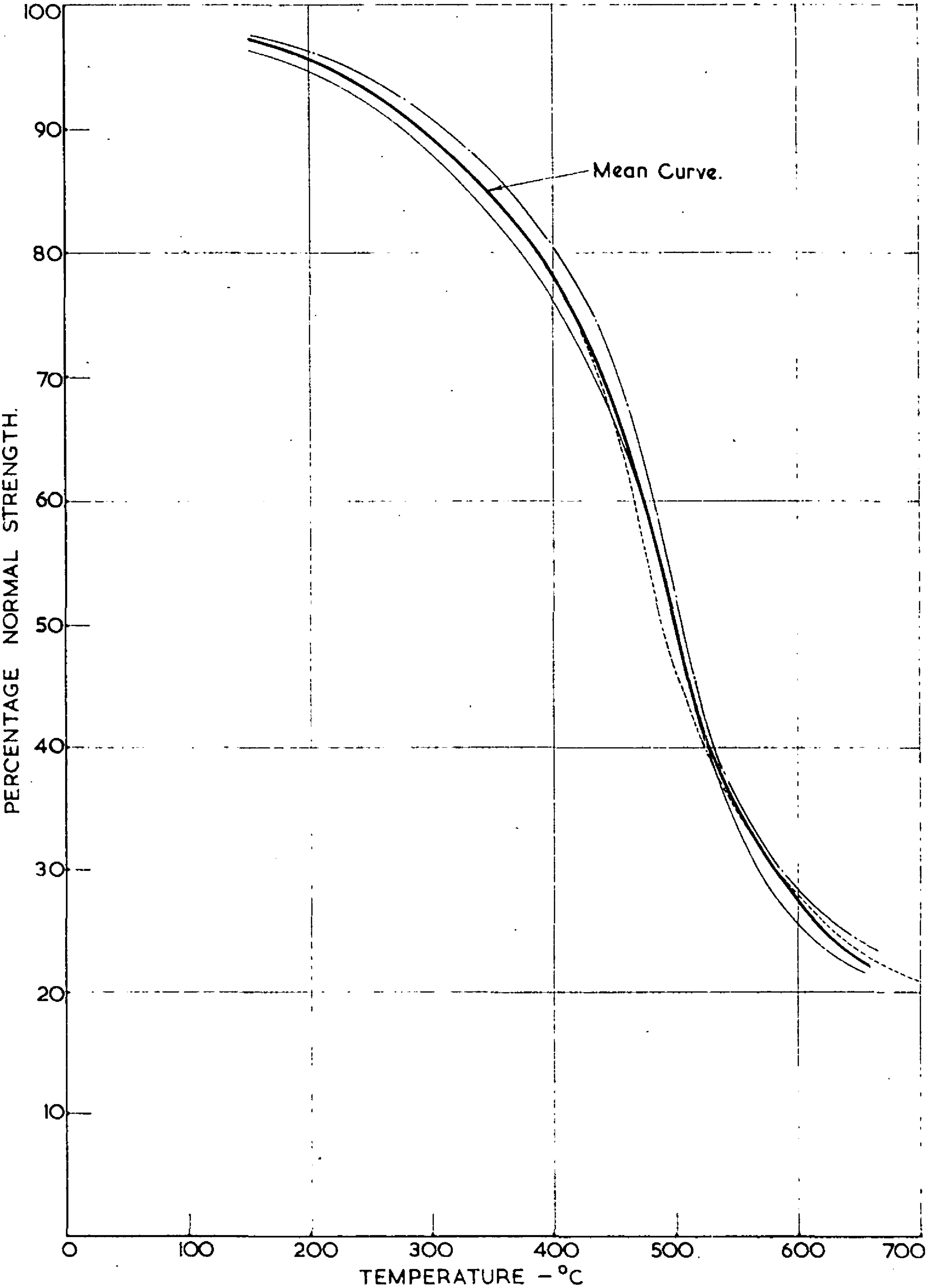


Concrete Mix — 1 : 3

w/c ratios — 0·50 ----------

0·45 —·—·—

0·40 ————

Testing condition — Constant temperature.

FIG. 8. EFFECT OF WATER / CEMENT RATIO ON TEMPERATURE STRENGTH RELATIONSHIP.

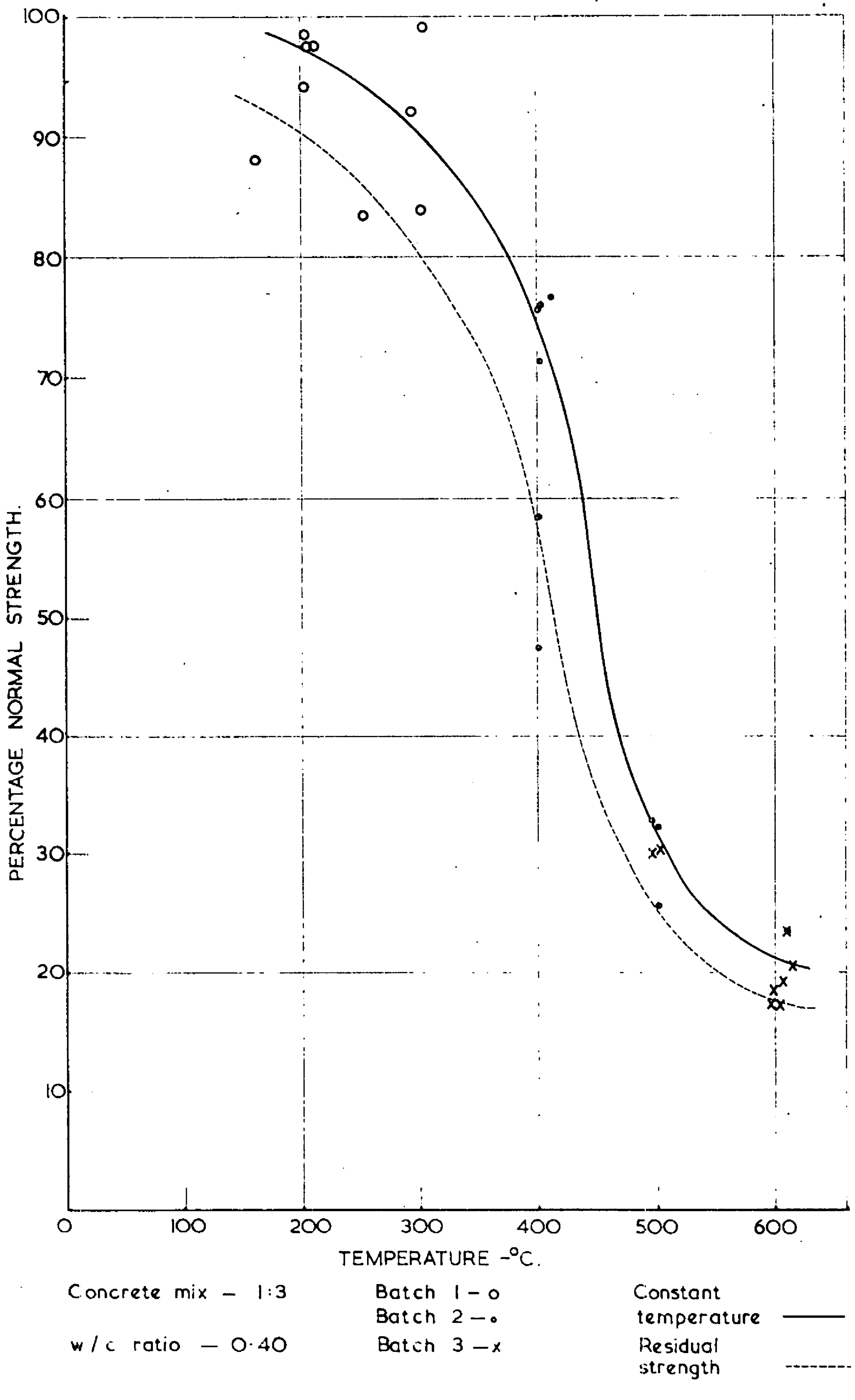
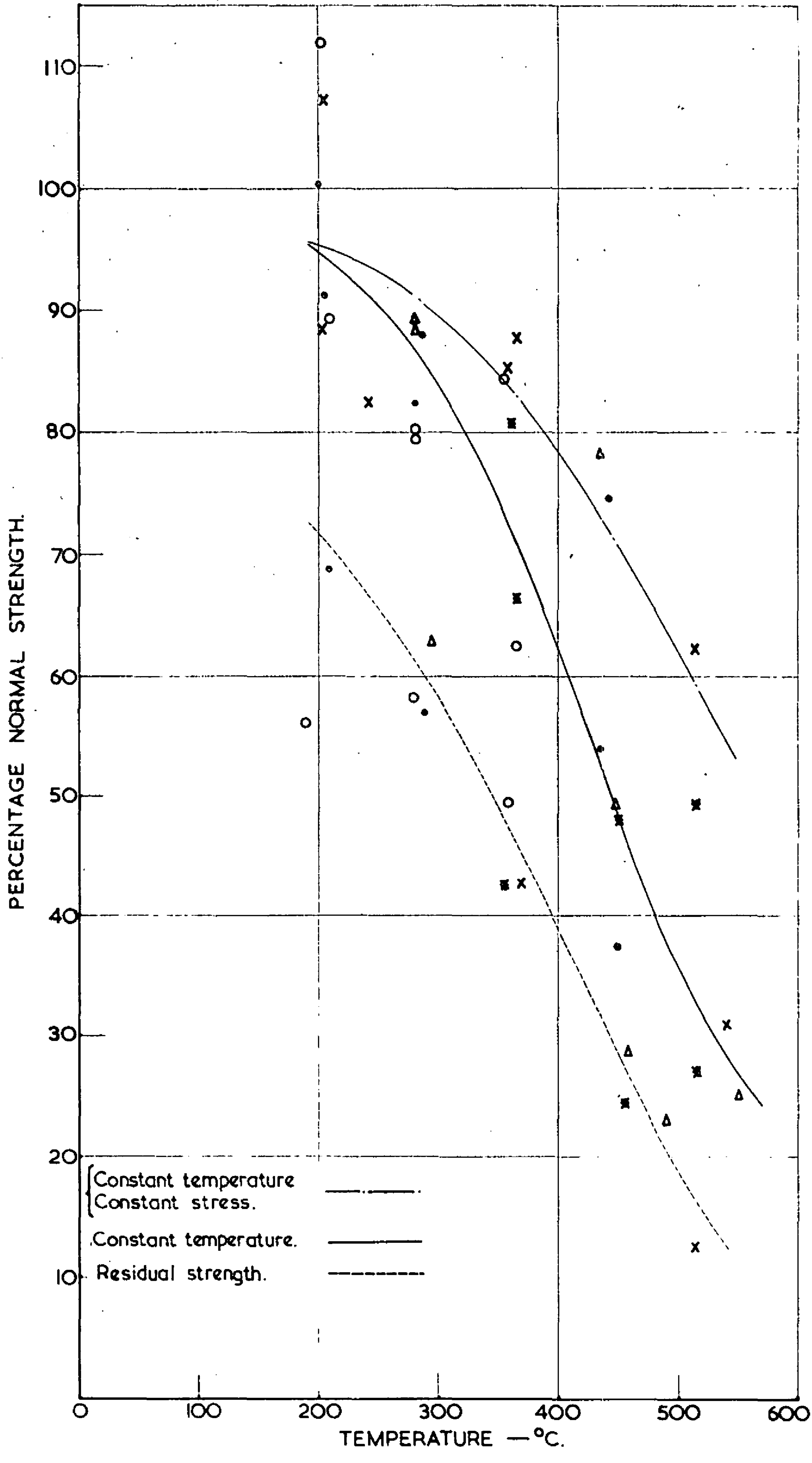


FIG. 9. TEMPERATURE – STRENGTH RELATIONSHIP FOR GROUP 4 SPECIMENS.



Concrete mix — 1: 4·5 Batch 1 — o Batch 3 — x

w / c ratio — 0·50 " 2 — • " 4 — Δ

" 5 — ✱

FIG. 10.

TEMPERATURE – STRENGTH RELATIONSHIP FOR GROUP 5 SPECIMENS.

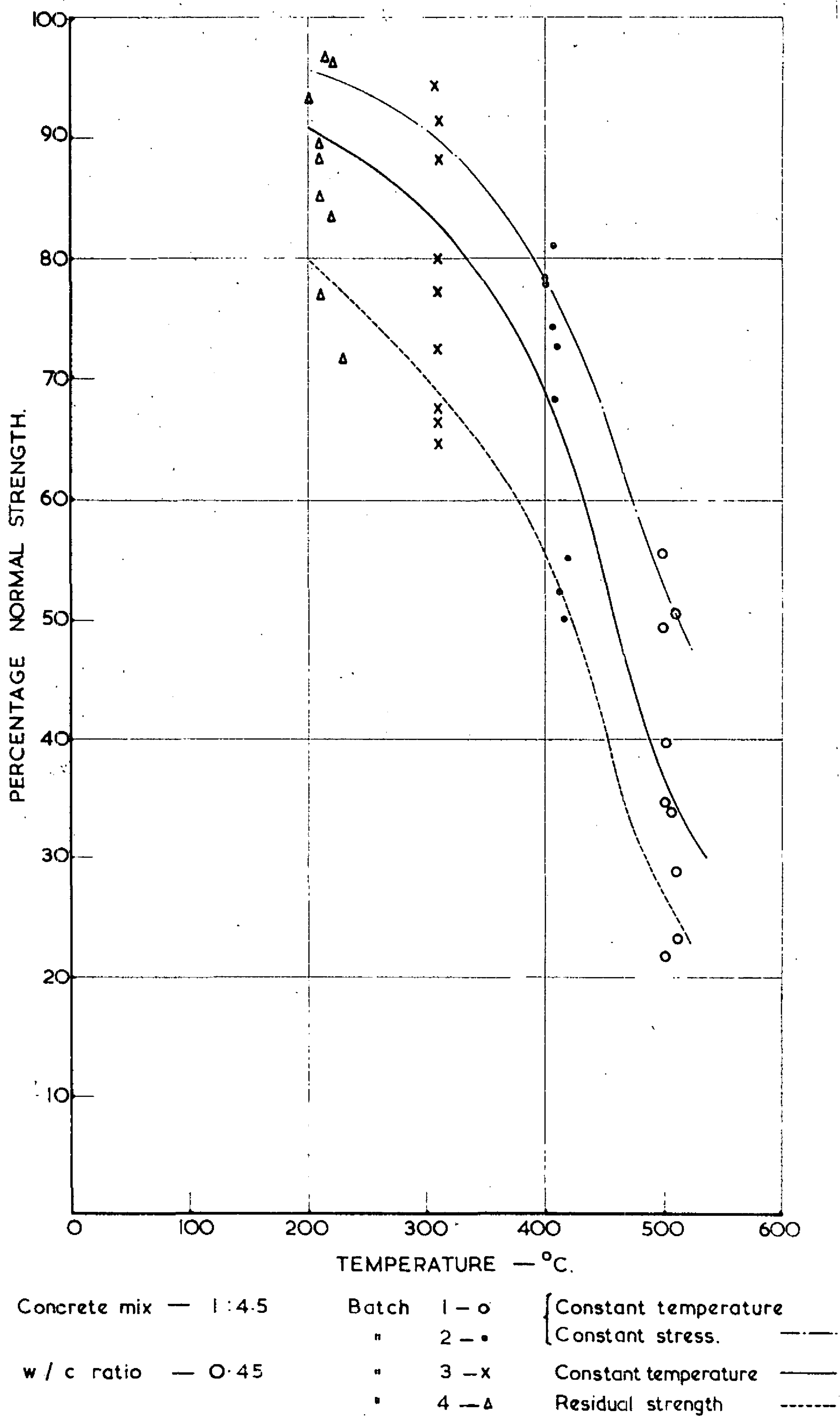


FIG. 11.

TEMPERATURE – STRENGTH RELATIONSHIP FOR GROUP 6 SPECIMENS.

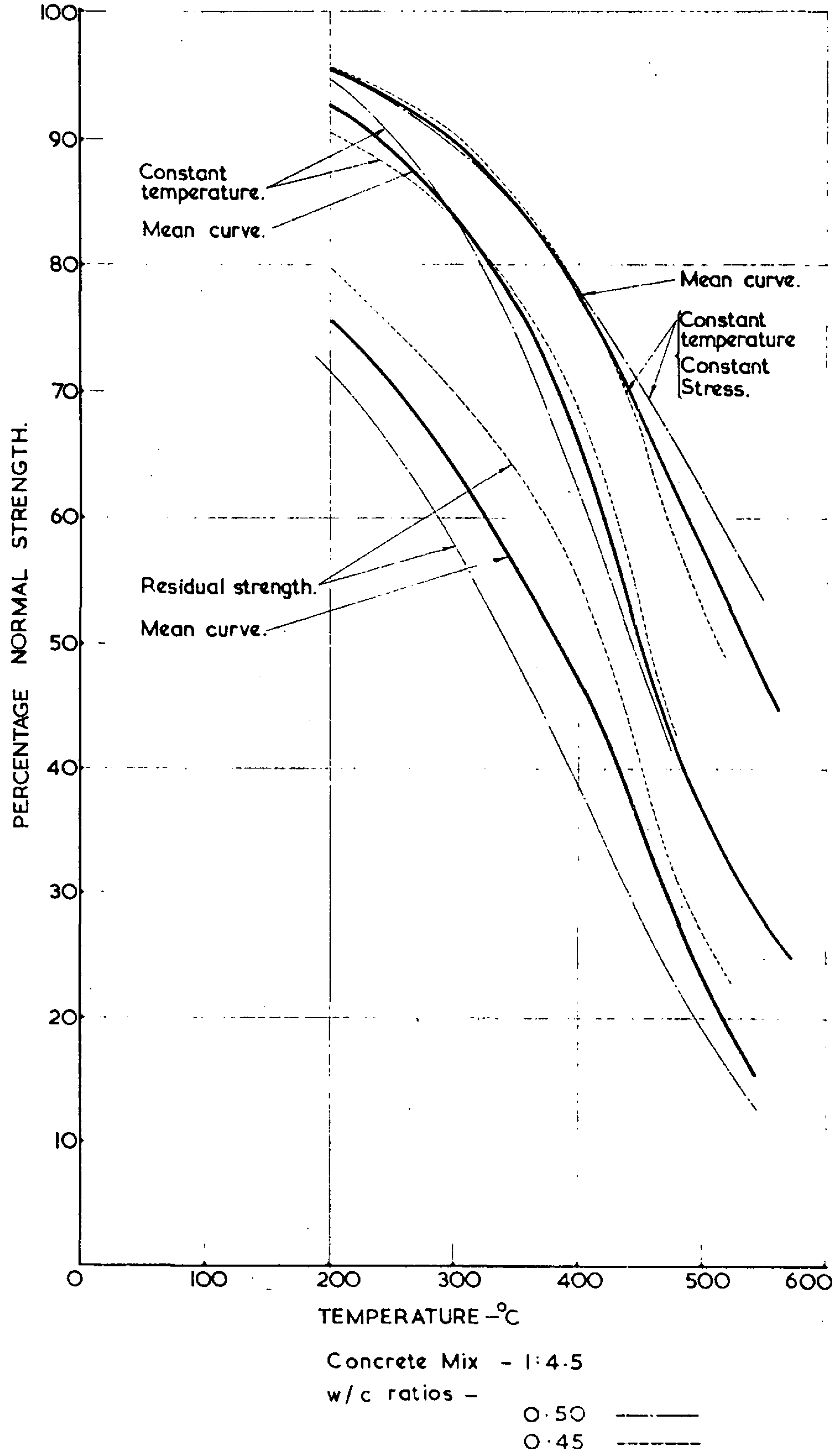
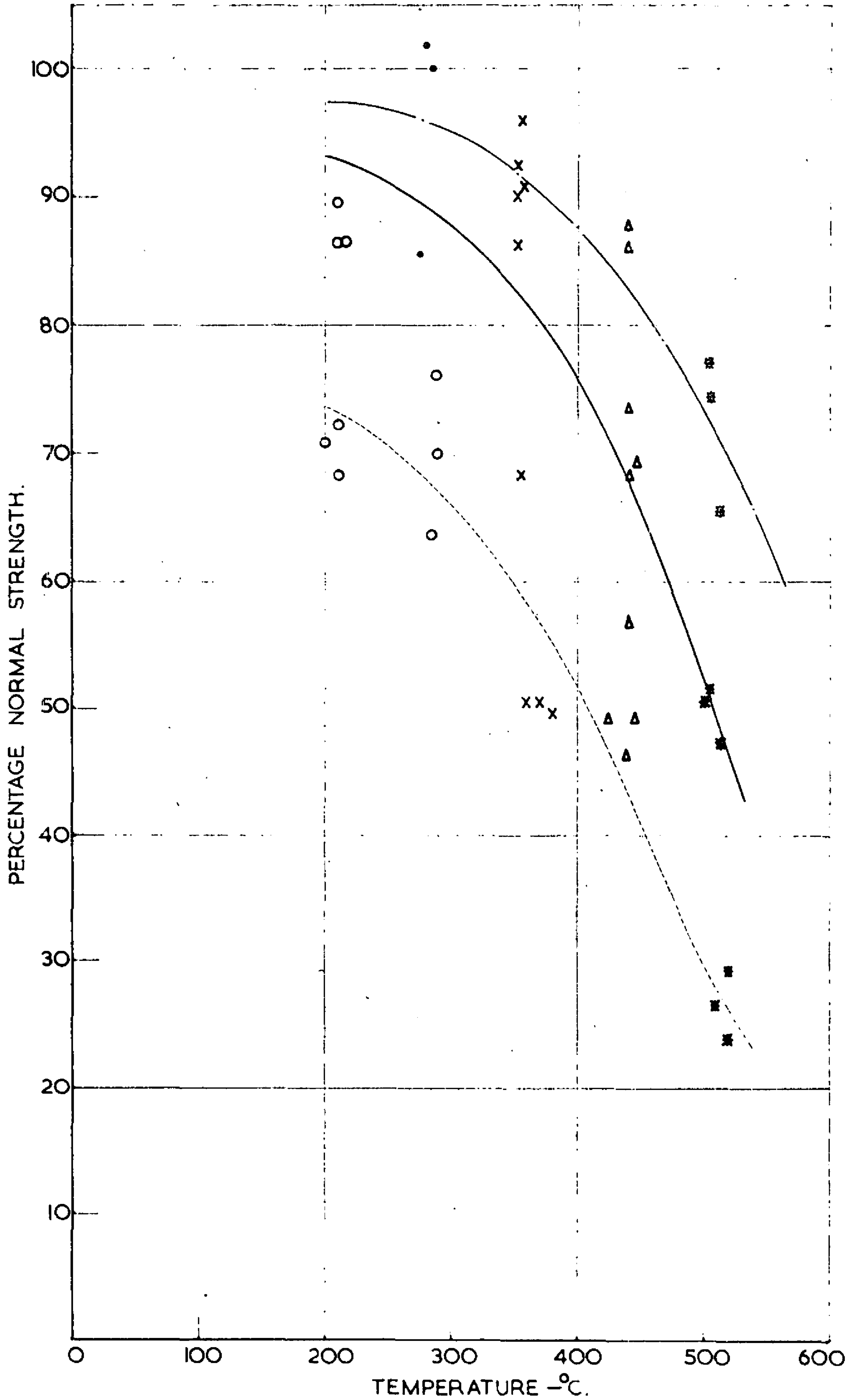


FIG. 12. TEMPERATURE – STRENGTH RELATIONSHIP FOR 1:4·5 MIX CONCRETE.



Concrete mix – 1:6

w/c ratio – 0·65

Batch 1 – o
" 2 – •
" 3 – x
" 4 – Δ
" 5 – ✱

Constant temperature
Constant stress. ———·———
Constant temperature. ————————
Residual strength. - - - - - - - -

FIG. 13.

TEMPERATURE–STRENGTH RELATIONSHIP FOR GROUP 7 SPECIMENS.

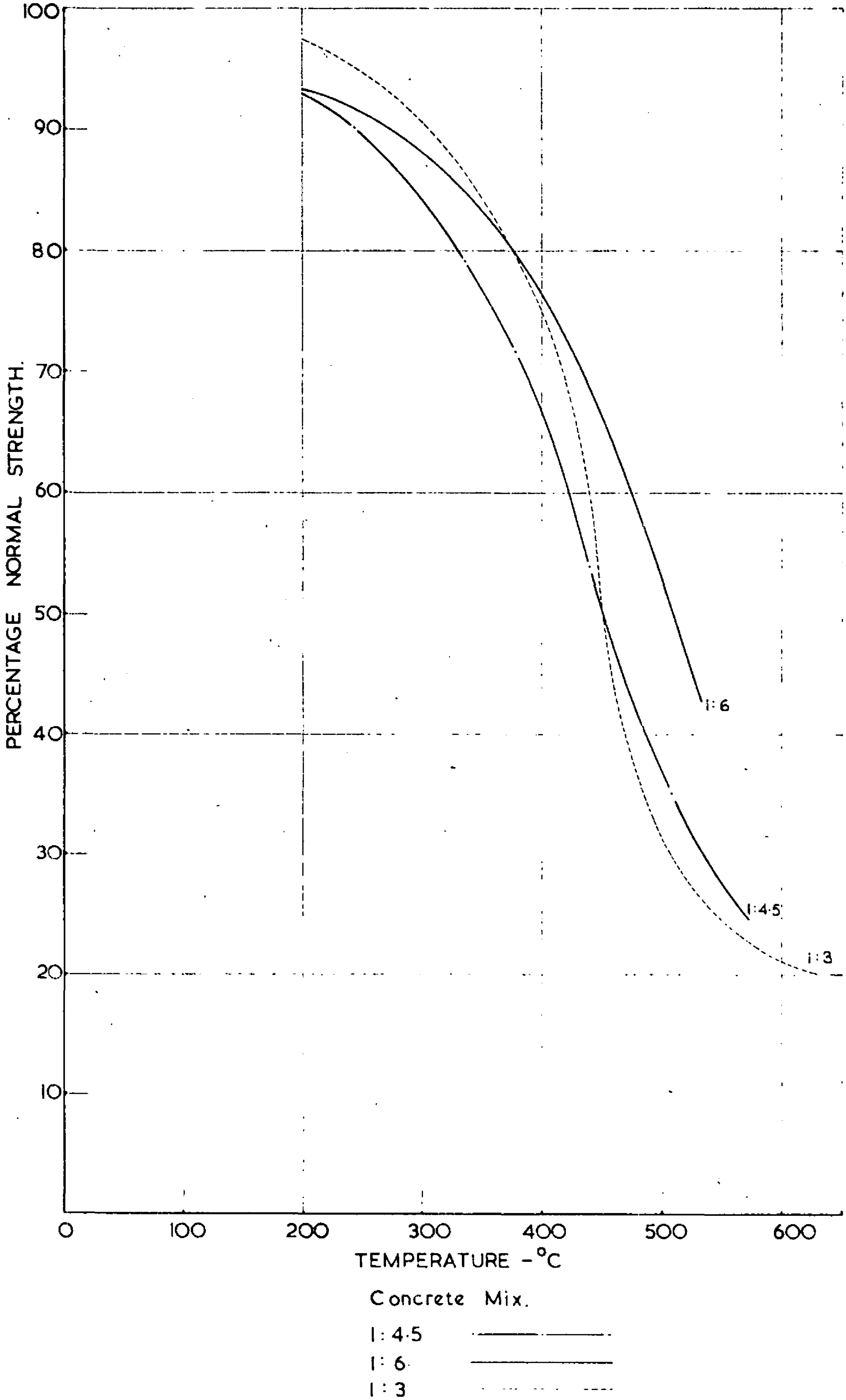


FIG. 14. CONSTANT TEMPERATURE STRENGTH CURVES FOR DIFFERENT CONCRETE MIXES.

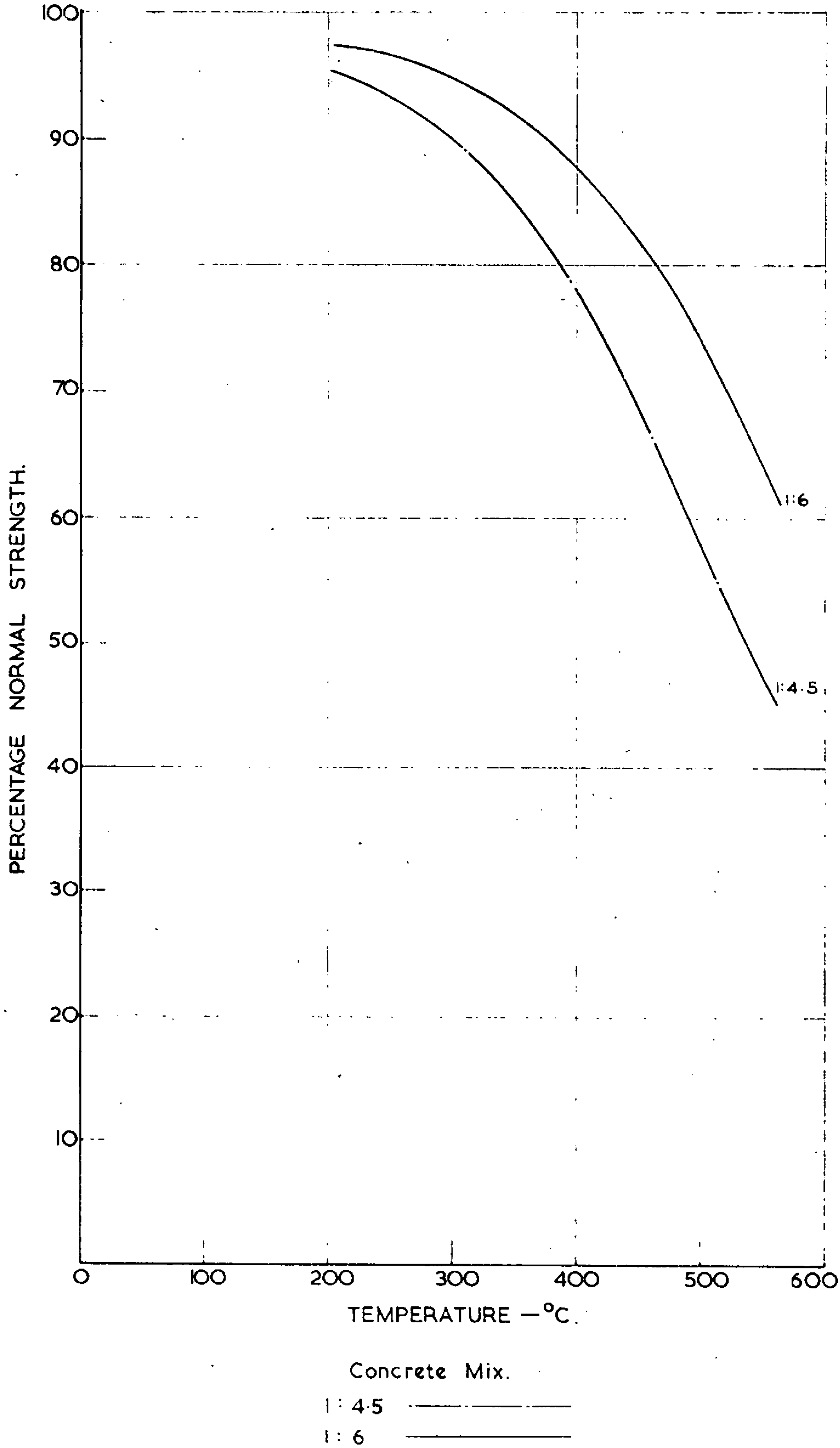


FIG. 15. CONSTANT TEMPERATURE — CONSTANT STRESS CURVES FOR DIFFERENT CONCRETE MIXES.

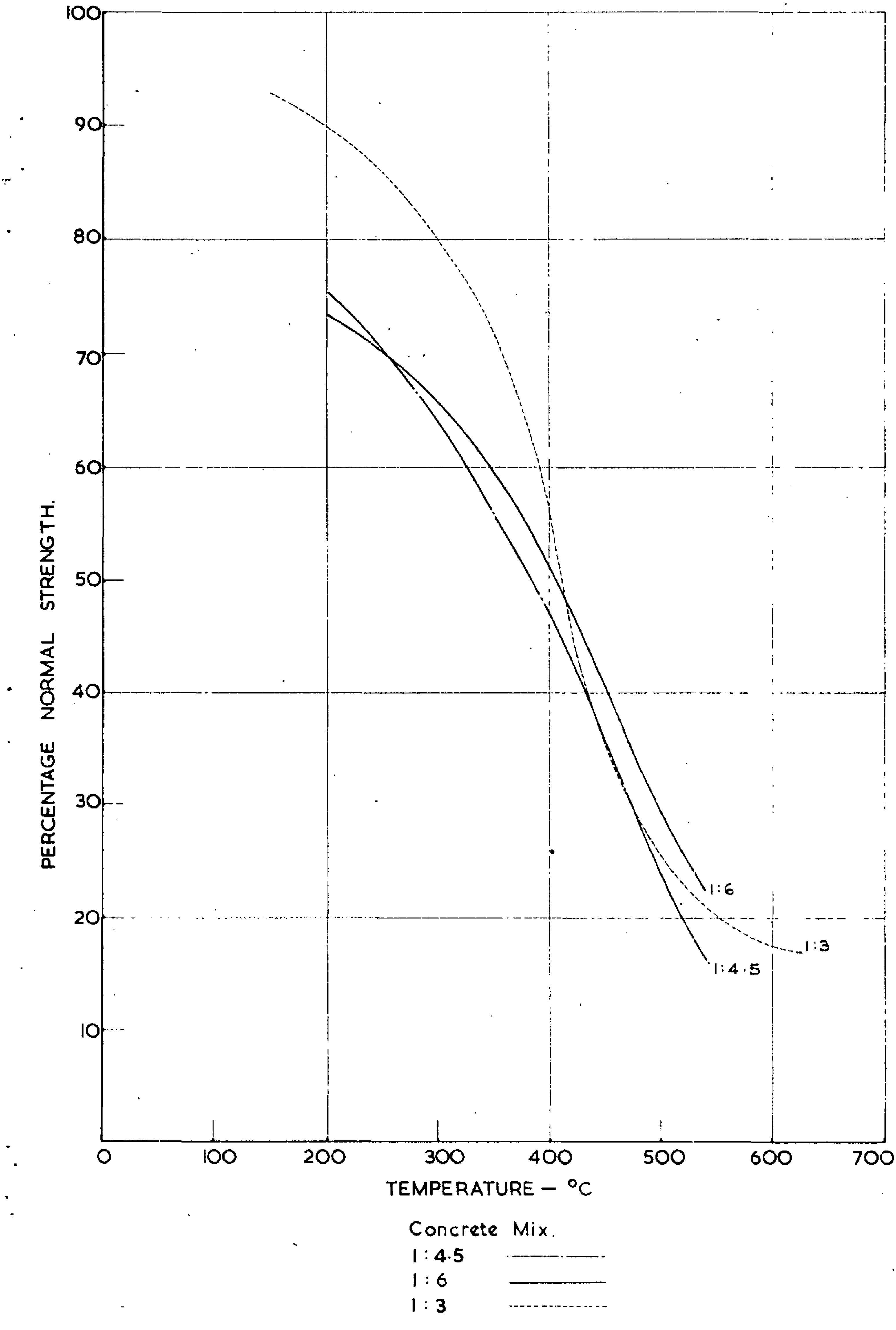


FIG. 16. RESIDUAL STRENGTH CURVES FOR DIFFERENT CONCRETE MIXES.

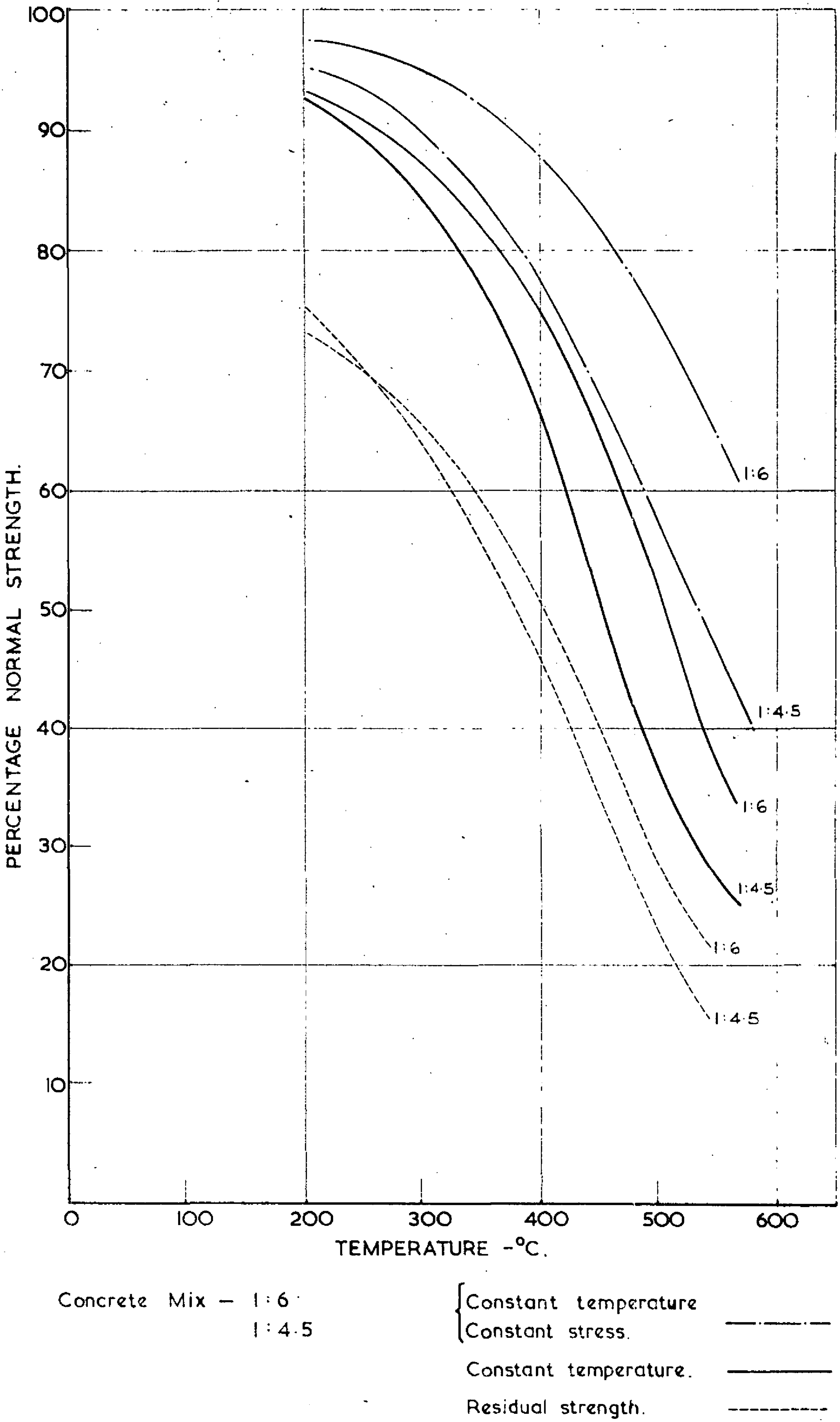


FIG. 17.

EFFECT OF TESTING CONDITIONS ON DIFFERENT CONCRETE MIXES