Zeitschrift: IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht

Band: 3 (1948)

Artikel: The deterioration of concrete: some factors affecting the resistance of concrete to frost action

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DOI: https://doi.org/10.5169/seals-4010

IIa4

Destruction du béton : Effet de l'influence néfaste du gel

Betonschäden : Nachteilige Einflüsse in bezug auf die Frostbeständigkeit

The deterioration of concrete : Some factors affecting the resistance of concrete to frost action

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Introduction

The resistance of concrete to damage by frost action varies considerably and depends partly on the type and proportions of the materials used in the mix and partly on the degree of exposure and moisture conditions to which the concrete is subjected. The action of frost in disintegrating concrete has already been explained (1). This paper describes further experiments carried out subsequent to those described by Collins, to determine the effect of the type of materials used, the grading of aggregate, and the mix proportions, including water-cement ratio. The tests were made on 4-in (10.2-cm) cubes which were subjected to daily cycles of freezing in the laboratory.

Description of test to determine the frost resistance of various types of concrete

The tests were designed to determine the effects of the following factors on the frost resistance of concrete : water-cement ratio, cement content, aggregate grading, type of aggregate and use of admixtures.

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(1) A. R. Collins, *The frost resistance of concrete* (*Journal of the Society of Chemical Industry*, August 1943, *62*, 113-116).
A. R. Collins, *The destruction of concrete by frost* (*Journal of the Institution of Civil Engineers*, November 1944, *23*, [1], 29-41).
T. C. Powers, *A working hypothesis for further studies of frost resistance of concrete* (*Journal of the American Concrete Institute*, 1945, *16* [4], 245-72).

The concrete was made under well controlled laboratory conditions. The materials were batched by weight, and mixing was carried out in a horizontal pan type mixer. Slump and compacting-factor tests were made to measure the workability. Three mixes were normally made for each type of concrete, and from each of these three mixes about thirty 4-in (10.2-cm) cubes were cast. These were thoroughly compacted in two layers by means of an electric vibrating hammer. The cubes remained in their moulds for about 24 hours, being covered with wet mats during this period. After being demoulded the cubes were placed in water for a further period of six days.

At an age of seven days about half the cubes were subjected to daily cycles of freezing and thawing and the remaining specimens were stored in water at 14° C. until they were due for test. The cubes in the freezing tests were frozen in air for 16 hours (with a prolonged cycle of 40 hours at week-ends) in a cold room at a temperature of −20° Centigrade. Thawing was done by placing the cubes in water tanks at a temperature of about 14° Centigrade for 8 hours. At periodic intervals cubes were removed for crushing strength tests, after being given an additional 24 hours thawing in water and the corresponding cubes cured at normal temperatures were also tested at the same time. The crushing strength tests were made by placing each cube on its side as cast in the testing machine and applying the load at a rate of 2 000 lb/sq.in per min. (141 kg/sq.cm per min.).

Records were kept of the ages of any cubes that disintegrated before being due for test. If no such disintegration occurred the tests were continued for a total period of six months.

Mix proportions. Materials and aggregate gradings used in the tests

Table 1 gives details of the proportions and materials used in the various mixes. In some cases where similar mixes were required in two different series of experiments, a single mix was used for both. All the proportions given are by weight of dry materials. Details of the aggregate gradings are given in fig. 5.

Results of tests

The results of the tests are given in figs. 1-4 and 6-8 where the crushing strength of the cubes cured at normal temperatures as well as those subjected to freezing and thawing are plotted against age in days and number of freezing cycles. Most of the crushing strengths are the average from tests on one test cube from each of three mixes. The age at which it was decided that complete disintegration had occurred often varied considerably among cubes from the same mix, and the point at which the curve crosses the line of zero strength represents the average age of disintegration.

In order to enable the results of tests on different mixes to be more readily compared, a method has been used by which the durability of each mix is expressed by a single number. This is called the « durability factor » and is the ratio of an area under the curve of crushing strength after freezing and thawing divided by an area formed by the crushing strength curve

Effect of	Mix Proportions* (By Weight)	N° of Mixes Made	Matérials	Durability Factor	Remarks
Water-Cement Ratio	1 : 2 : 4/0.5	3	Flint River Gravel (Grading Curve A in fig. 5)	1.06	Similar aggregate, gradings and cement content
	1 : 2 : 4/0.6	3		0.62	
	1 : 2 : 4/0.7	3		0.29	
	1 : 2 : 4/0.8	3		0.20	
Cement Content	1 : 2 : 4/0.6	3	Flint River Gravel (Grading Curve A in fig. 5)	0.82	Similar aggregate, gradings and water-cement ratios
	1 : 2 1/2 : 5/0.6	3		1.26	
	1 : 2 : 4/0.8	3		0.20	ditto
	1 : 3 : 6/0.8	3		0.53	
Aggregate Grading	1 : 2 : 4/0.6	3	Flint River Gravel — Grading Curve B	0.82	Similar aggregates, cement content and water-cement ratios
	1 : 3 : 3/0.6	3	Flint River Gravel — Grading Curve C	1.01	
	1 : 4 : 2/0.6	3	Flint River Gravel — Grading Curve D	1.38	
Type of Aggregate	1 : 2 : 4/0.6	1	Ketton limestone	1.14	Similar mix proportions
	1 : 2 : 4/0.6	1	Swanworth limestone	1.90	
	1 : 2 : 4/0.6	1	Rickmansworth chalk	0.01	
Admixtures	1 : 2 : 4/0.6	3	Flint River Gravel — Without Vinsol	0.98	Similar proportions and water-cement ratios, varying amount of Vinsol
	1 : 2 : 4/0.6	3	Flint River Gravel — With 0,02 per cent Vinsol	1.14	
	1 : 2 : 4/0.6	3	Flint River Gravel — With 0,05 per cent Vinsol	1.12	
	1 : 2 : 4/0.6	3	Flint River Gravel — Without Aluminium Powder	0.62	Similar proportions and water-cement ratios, varying amount of alumin. powder
	1 : 2 : 4/0.6	1	Flint River Gravel — With 0.0105 per cent Al	1.37	
	1 : 2 : 4/0.6	1	Flint River Gravel — With 0.0404 per cent Al	1.34	

* Expressed as Cement : fine aggregate : coarse aggregate/water-cement ratio.

TABLE I. *Details of the proportions and materials used in the various mixes.*

after normal curing. A somewhat similar method has already been used by Stanton Walker [2], who used the reduction in elastic modulus as his criterion instead of the crushing strength. The method of calculation is given in the Appendix.

Discussion of results

In considering the results of the tests, it should be remembered that the tests were carried out under very severe conditions, starting when the concrete was at an age of only 7 days. Concrete which satisfactorily withstands 25 to 35 cycles of freezing under these conditions will probably withstand satisfactorily the normal weather conditions met with in Great Britain for an indefinite period.

When a sound aggregate is used, such as a flint or granite, there appears to be little chance of frost affecting the aggregate itself, but disintegration of the cement paste may occur. The resistance of the cement paste

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(2) Stanton WALKER, *Freezing and thawing tests of concrete made with different aggregates (Journal of the American Concrete Institute 15* [6], 573-77).

to frost damage is dependent upon its strength, the pore structure and the presence and availability of water.

a) *Effect of water-cement ratio.* The results, given in fig. 1 show that the water-cement ratio has a very great effect on the durability of concrete. A change in water-cement ratio from 0.5 to 0.8 in mixes which were alike in other respects, resulted in a change from concrete which satisfactorily resisted over 110 cycles of freezing without failure, to one in which complete disintegration occurred after 19 cycles.

The strength of the cubes subjected to freezing cycles and those cured at normal temperatures are plotted against the water-cement ratio in fig. 2 for various ages.

b) *Effect of cement content.* The results of tests on mixes having different cement contents but alike in other respects are given in fig. 3. The lean mixes (i.e. those containing less cement) were more resistant to frost action than richer mixes with the same water-cement ratio. For a water-cement ratio of 0.6, a reduction in the cement content from 1 : 6 to 1 : $7\frac{1}{2}$ increased the durability factor from 0.82 to 1.26, and for a water-cement ratio of 0.8 a change in cement content from 1: 6 to 1 : 9 resulted in an increase in the durability factor from 0.20 to 0.53.

The explanation of the effect of cement content on the durability of concrete is thought to be very similar to that of aggregate grading and both of these factors are discussed together under the next heading.

c) *Effect of aggregate grading.* The results of tests on several series of mixes, each having similar cement contents and water-cement ratios but with different aggregate gradings, are given in fig. 4. The corresponding aggregate gradings are given in fig. 5. All these results show that a more durable mix was produced by using a higher sand content in the concrete.

The following is a suggested explanation of these results which would

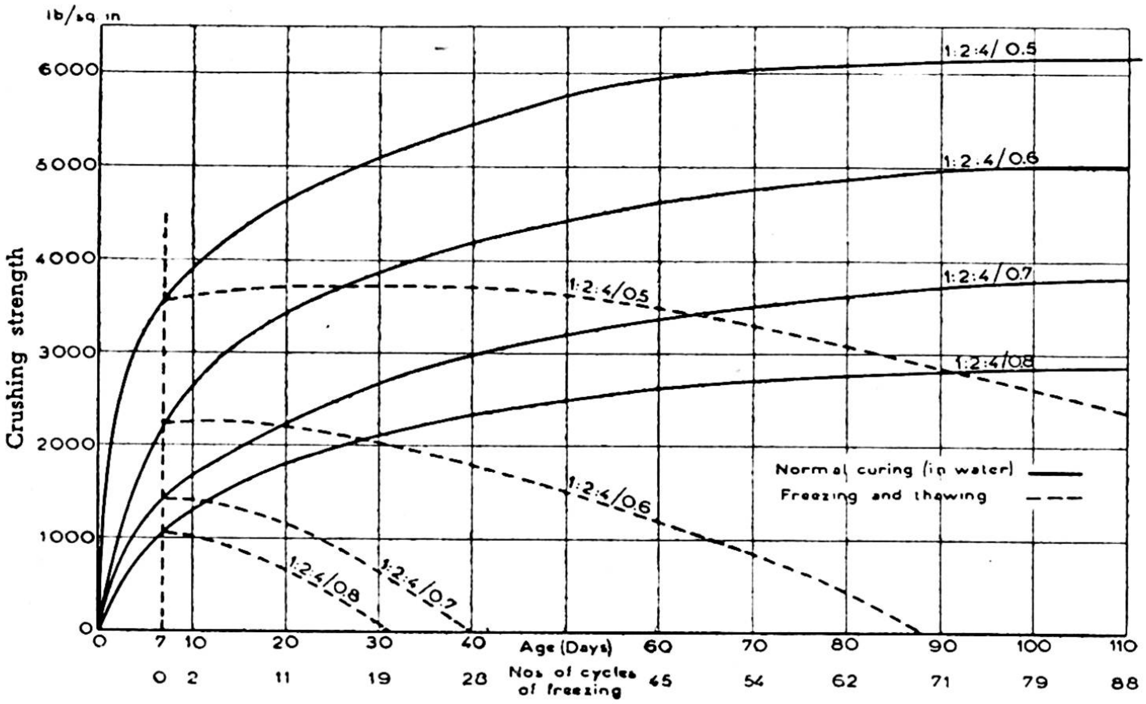


Fig. 1. The effect of water-cement ratio on the frost resistance of concrete.

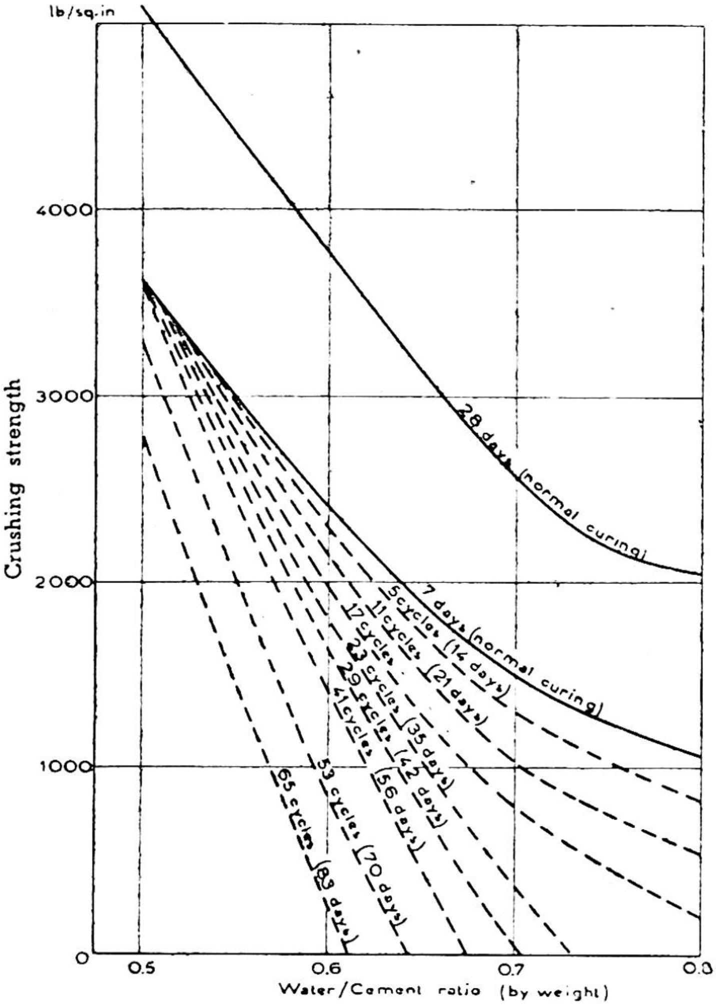
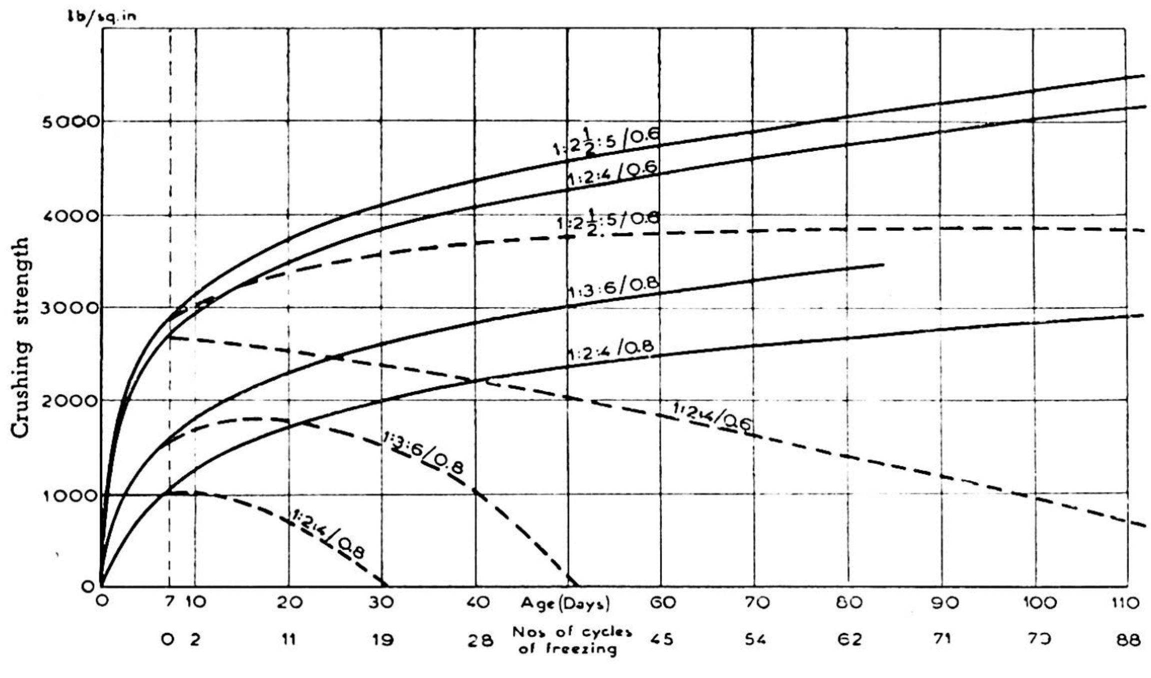


Fig. 2. Relation between crushing strength and water-cement ratio for various numbers of freezing and thawing cycles.

Fig. 3. The effect of cement content on the frost resistance of concrete.



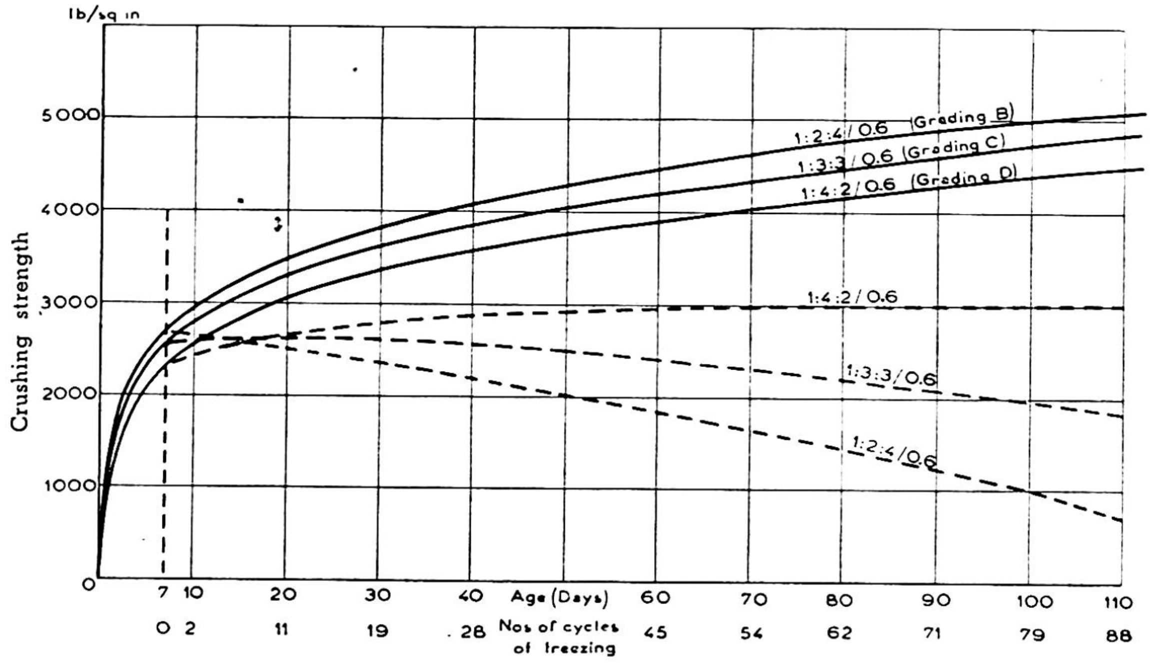


Fig. 4. Effect of aggregate grading on the frost resistance of concrete.

account for the effect of aggregate grading and cement content on the durability of concrete. For a given weight of aggregate, a material having a higher proportion of sand or fine gradings will have a larger total surface area than a material containing less of the small sizes. The cement paste may be considered as being used in two ways, some filling the voids between the aggregate particles and the remainder coating the aggregate particles with a layer of cement paste, the thickness of which depends upon the surface area of the aggregate and the amount of paste available.

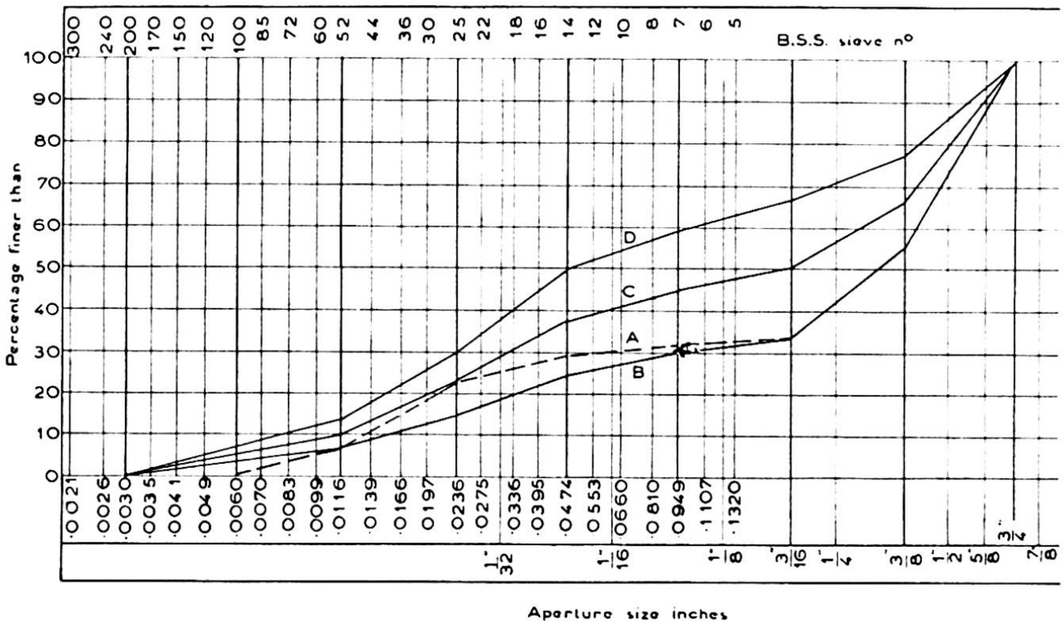


Fig. 5. Grading curves of aggregates.

For similar types of aggregate the percentage volume of voids differs only slightly and therefore the amount of paste left to coat the varying surface areas of the different gradings will be approximately constant and will result in films of cement paste of different thicknesses.

A thin film of cement paste between the aggregate particles will assist in resistance to frost damage in three ways : the structure as a whole is likely to be physically stronger, the total amount of water available will be smaller (assuming the aggregate to have a lower water absorption than the cement paste) and the flow of water to growing ice crystals will be reduced.

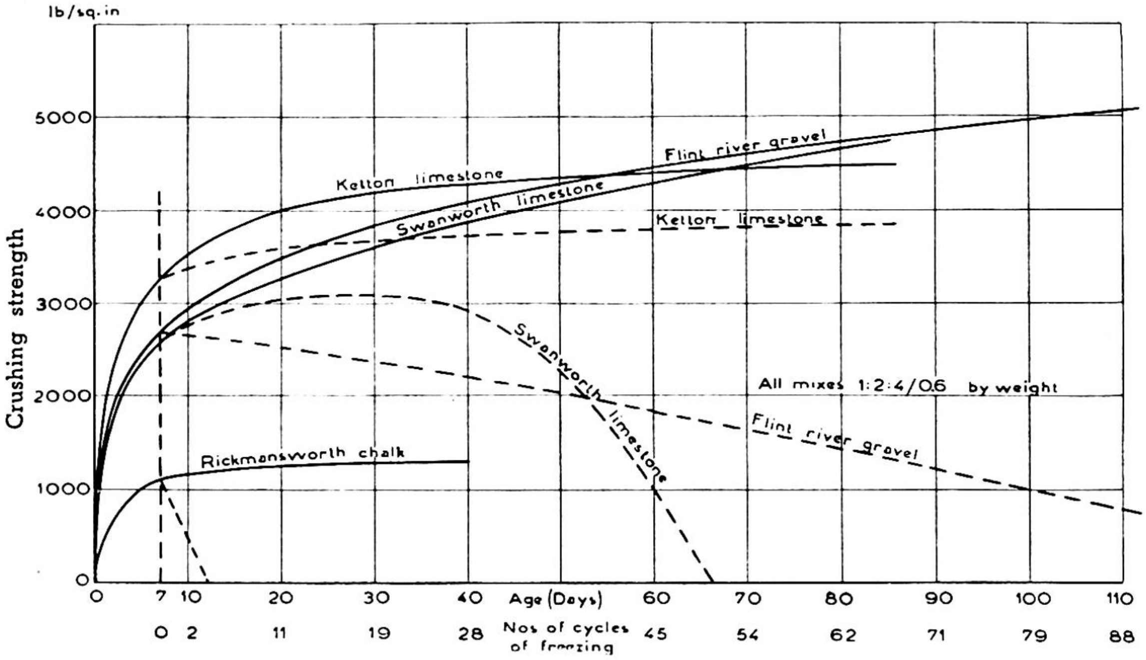


Fig. 6. Effect of limestone and chalk aggregates on the frost resistance of concrete.

d) *Effect of type of aggregate.* Tests were made on concrete containing chalk and limestone aggregate. The chalk was of medium hardness and two types of limestone were used, one of a porous oolitic type and the other a fairly hard limestone. The results are shown in fig. 6.

The concrete made with chalk aggregate disintegrated after 4 cycles of freezing and had a durability factor of 0.04. The limestone mixes were much more durable and both types compared favourably with flint gravel. The hard type had a durability factor of 0.90 and the porous oolitic type a factor of 1.14 but in the latter case the high figure may be due to the limestone having absorbed some of the mixing water and so reduced the effective water-cement ratio.

The special case of the cement grouted road using chalk as the aggregate is referred to later.

e) *Effect of admixtures.* The effects of two different types of admixture on the frost resistance of concrete are illustrated in figs. 7 and 8. These consisted of Vinsol resin and aluminium powder and gave the concrete

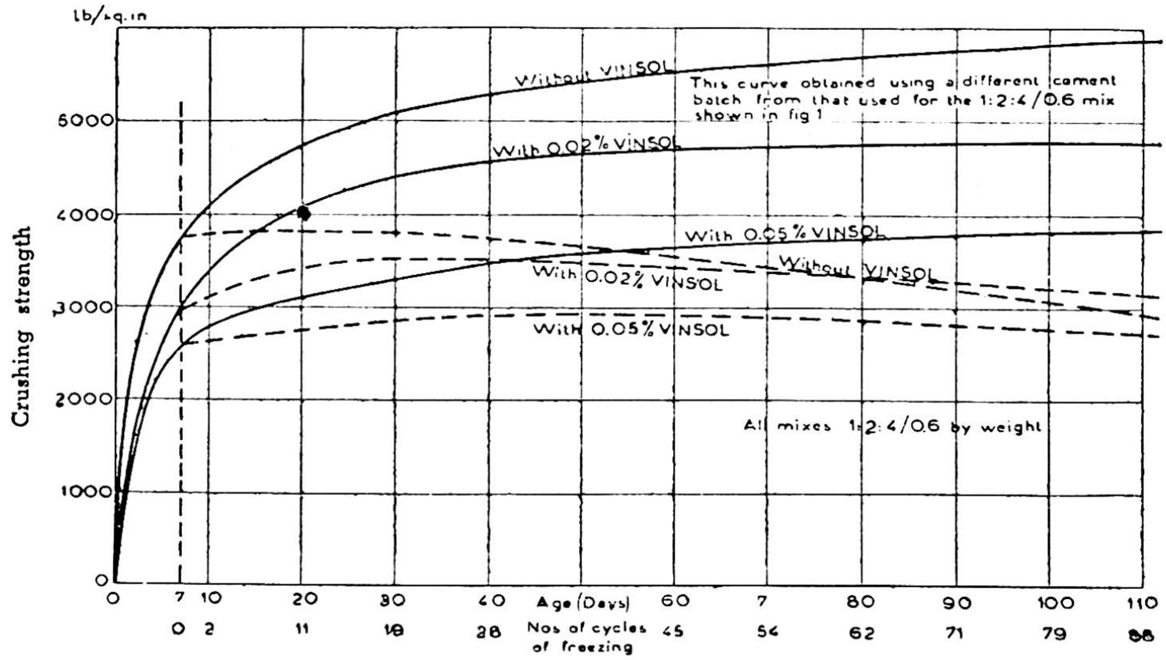


Fig. 7. Effect of addition of Vinsol resin on the frost resistance of concrete.

an improved durability as well as increasing the workability, but in both cases the crushing strength was reduced.

The durability factors and crushing strengths at 28 days of mixes containing varying amounts of Vinsol resin were as follows :

0.98 and 5 010 lb/sq.in with no Vinsol,
1.14 and 4 320 lb/sq.in with 0.02 per cent Vinsol (by weight),
1.12 and 3 370 lb/sq.in with 0.05 per cent Vinsol (by weight).

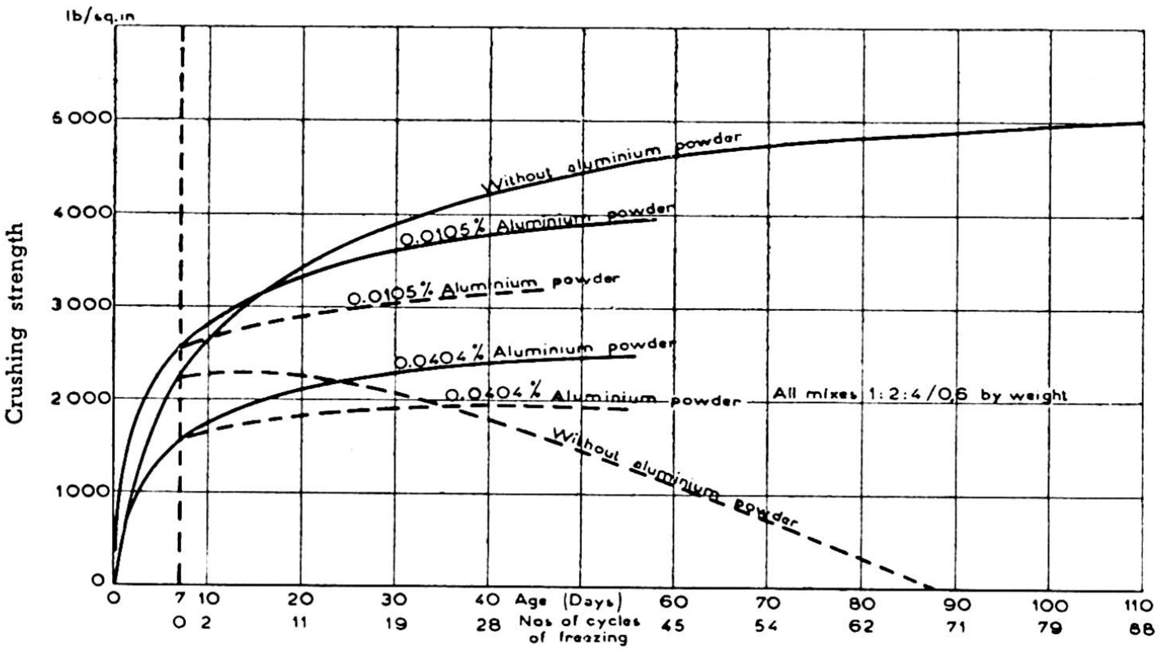


Fig. 8. Effect of addition of aluminium powder on the frost resistance of concrete.

If advantage is taken of the improved workability by reducing the water-cement ratio to the point where the workability of the Vinsol concrete is the same as that of normal concrete, it is likely that the crushing strength would not be appreciably reduced and even better resistance to frost action would result.

The durability factors and 28-day crushing strength of mixes containing aluminium powder were as follows :

0.62 and 3 700 lb/sq.in with no aluminium powder,
1.37 and 3 500 lb/sq.in with 0.0105 per cent aluminium powder,
1.34 and 2 100 lb/sq.in with 0.0404 per cent aluminium powder.

Again, the smaller proportion of aluminium powder gave greater strength and durability.

The improved resistance to frost damage resulting from the use of admixtures was comparatively small and under laboratory conditions could be equally well obtained by using a lower water-cement ratio provided the concrete could still be thoroughly compacted. Under field conditions, where control over mixing cannot be so rigid, there would be advantages in using the admixtures, especially if the water-cement ratio is reduced relative to that of normal concrete to maintain the same degree of workability.

It will be noticed that, for a 1 : 2 : 4/0.6 mix, higher strengths are obtained for the mixes whose results are given in fig. 1 than for those given in fig. 7 : this applies both to cubes cured normally in water and to cubes subjected to freezing cycles. This is probably accounted for by the fact that two different batches of cement were used and shows that, for cements of the same type, a variation in the frost-resisting properties may occur from batch to batch. To eliminate the effect of cement variation, all mixes made to determine the effect of one particular variable were made from the same batch of cement.

Recommendations for the design of concrete mixes to resist damage by frost action

The results illustrated in figs. 1-4 and 6-8 indicate that for concrete to have a good resistance to damage by frost action the following conditions should be fulfilled :

The water-cement ratio should be as low as possible consistent with the ability to compact it fully;

An aggregate which will produce a mix of good workability should be used;

The aggregate itself should be durable;

The cement content should be kept to a minimum.

The durability may be improved by the use of some types of admixture, particularly Vinsol resin.

It has been seen that higher sand contents in a mix gave greater durability when the water-cement ratios were similar. In practice a given degree of workability is generally required and the gradings with the higher sand content would require a higher water-cement ratio if the workability is not to be reduced. As the water-cement ratio has a much bigger influence on the durability of concrete than the thickness of the cement paste film, it is always preferable to keep the water-cement ratio as low as possible. The grading which produces the mix of greatest workability should therefore be used because of its indirect effect of reducing the water-cement ratio necessary.

Aggregates which have a high silt content or which are composed of very angular particles, both of which reduce the workability of the mix, should be avoided if possible.

The use of chalk as a concrete aggregate

Experiments were carried out at the Road Research Laboratory during the war to examine the conditions in which a chalk aggregate could be made to resist frost effects. The results obtained suggest that, in areas where chalk is the only material economically available as aggregate, it may be used for, say, secondary roads provided that certain precautions are taken during construction. Since chalk is generally too soft to be tumbled about in a concrete mixer without powdering, it was broken to 1 in $-2\frac{1}{2}$ in ($2\frac{1}{2}$–$6\frac{1}{2}$ cm) in size and placed on the road bed. Cement-sand grout of fluid consistence was then poured into the voids to make a solid mass.

In carrying out the experiments, specimens of grouted chalk, 18 in square × 6 in deep (46 cm × 15 cm) were subjected to freezing from the top surface only, the sides and bottom being insulated by means of granulated cork. The cycle consisted of 16 hours at $-10°$ C. and 8 hours in water at 14° C. By this means various methods of preventing frost damage to cement-grouted chalk concrete were examined, including :

Coating the chalk lumps with a protective layer such as tar, pitch, sodium silicate, sump oil or ferric steorate;

Using a grout containing admixtures such as Vinsol, bituminous emulsion or motor oil;

By covering the top surface of the specimens with a thin layer of grout, or grout with hard stone chippings pressed in, or by applying a thin surface coating of bituminous material;

By covering all the surfaces, i.e. top, bottom and sides with a layer of grout approximately $\frac{1}{2}$ in thick.

The last method was the most successful one. This may be carried out in practice in the following manner : The formation is prepared and the side forms are set for a sufficient length to cover about three days' work. Grout is then spread over the formation to a depth of approximately $\frac{1}{2}$ in, preferably being placed on waterproof paper, and allowed to harden for two or three days. Boards, $\frac{1}{2}$ in thick, are then attached to the inside of the forms. The next operation is to spread the chalk aggregate over the hardened layer of mortar to within $\frac{1}{2}$ in of the finished surface level. This is then grouted to fill the interstices of the chalk and the surface given a rough screed finish. If the chalk is sufficiently dry to absorb water rapidly from the grout, it will cause the grout to lose its fluidity before it has penetrated the full thickness and it is therefore necessary to water the chalk well before grouting. As soon as the grout is sufficiently hard (say after 3-4 hours) remove the side boards and fill the gaps with grout and continue grouting over the whole area until within $\frac{1}{4}$ in of the finished surface level. Stone chippings are then applied to provide a wearing surface.

A section of road was laid in this manner in England during the war at a site used by logging and by ammunition lorries. After two severe winters it was still satisfactorily carrying the traffic. Similar roads constructed without the protective coating disintegrated badly during the first winter of exposure.

Conclusions

The resistance of concrete to frost action is primarily dependent upon the water-cement ratio, the resistance to frost damage increasing as the water-cement ratio is reduced;

Variations in the quality of the cement from batch to batch affect the frost resistance of the concrete, and concrete made from a cement which gives a higher strength has a greater resistance to damage by frost action;

For mixes of a given water-cement ratio the durability is improved by the use of a low cement-aggregate ratio, although this will reduce the degree of workability of the mix;

The effect of the water-cement ratio on the resistance of concrete to frost action is very much greater than that of the cement-aggregate ratio, and it is therefore preferable to use the lowest water-cement ratio possible even if this means increasing the cement-aggregate ratio to obtain sufficient workability;

Although the results show that for a given water-cement ratio a high sand content produces a more durable mix, it also reduces the workability. If a given degree of workability is required, it is preferable to reduce the sand content and thereby enable a lower water-cement ratio to be used as this has a much greater effect in improving the durability of concrete than the high sand content;

Concrete made from a hard flint aggregate failed by disintegration of the cement paste alone, the aggregate remaining undamaged;

Concrete made from chalk or porous limestone is liable to fail by disintegration of the aggregate itself and this may occur very rapidly, particularly in the case of chalk;

Cement-grouted chalk aggregate has given relatively good results in resisting frost damage, when surrounded by a layer of mortar;

Concrete made with fairly hard limestone aggregates and having a low water-cement ratio is fairly resistant to the effects of repeated cycles of freezing;

The use of some admixtures such as Vinsol resin and aluminium powder increases the frost resistance of concrete. They also increase the workability of the concrete and so enable the water-cement ratio to be reduced; this is an additional point in favour of the use of such admixtures.

Appendix

Method of calculating durability factors

The durability factor is determined as follows :

(1) The area under the strength curve for concrete subjected to freezing cycles, enclosed by the 7-day ordinate, the strength curve, the 84-day ordinate

and the base line is measured. If the concrete has disintegrated before reaching an age of 84 days then the area enclosed by the 7-day ordinate, the strength curve and the base line is used instead. The area is expressed in units of lb/sq.in × number of days.

(2) The strength at 7 days (i.e. the strength at the beginning of the freezing cycles) is multiplied by (84 − 7) days.

(3) The Durability Factor is the ratio of (1) divided by (2) and is in non-dimensional units.

In some cases, where the tests were not continued for 84 days, the durability factor was calculated up to the age at which the tests were stopped.

A durability factor of 1.00 would be obtained if there is neither gain nor loss of crushing strength when the concrete is subjected to freezing cycles, and is therefore a useful reference figure.

A durability factor greater than 1.00 indicates that some increase in strength occurred after freezing and thawing commenced.

Résumé

Des recherches ont été entreprises pour déterminer l'effet des considérations suivantes sur la résistance au gel du béton :

1° Proportion eau-ciment;

2° Teneur en ciment;

3° Granulométrie de l'agrégat;

4° Espèce d'agrégat;

5° Emploi de dosages.

Les essais étaient effectués sur des cubes de béton de 10,2 cm de côté; ceux-ci étaient soumis tous les jours à un cycle de congélation dans de l'air à une température de —20° centigrade, et de dégel dans de l'eau à une température de 14° centigrade. Les dégâts occasionnés par les cycles de congélation étaient mesurés par la réduction de la résistance à l'écrasement des cubes, et enfin par le nombre de cycles nécessaires à la désagrégation complète. Les résultats sont fournis par des séries de graphiques qui donnent d'une part la résistance des cubes à l'écrasement, d'autre part l'âge et le nombre de cycles de congélation. On peut exprimer ces résultats pour chaque genre de béton par un seul chiffre, dit « Facteur de Durabilité ». Une explication de l'effet de la teneur en ciment et de la granulométrie de l'agrégat sur la durabilité du béton est suggérée.

La comparaison entre des essais de laboratoire et des essais sur le chantier, souligne la sévérité des essais de laboratoire et la vitesse relative avec laquelle les résultats peuvent être obtenus. Des recommandations sont données concernant les conditions à imposer au béton pour lui permettre de résister aux dégâts de l'effet de gel. Les conclusions principales sont :

a) La durabilité du béton dépend premièrement de la proportion eau-ciment, et plus cette proportion s'abaisse, plus la durabilité augmente;

b) La durabilité est améliorée par l'application de mélanges qui comportent une basse teneur en ciment en rapport avec l'agrégat;

c) Quelques agrégats de craie et de pierre à chaux produisent un béton qui possède une résistance satisfaisante à l'action de congélation, pourvu qu'une faible proportion eau-ciment soit employée dans le gâchage;

d) Quelques additions qui produisent un entraînement d'air, fournissent un gâchage dont la durabilité et la maniabilité sont améliorées, mais en général ceci est accompagné d'une réduction de la résistance à l'écrasement.

Un cas spécial de l'effet d'un genre d'agrégat, est celui de l'usage de la craie dans la construction des routes à coulis de ciment : des essais étaient effectués pour déterminer les conditions dans lesquelles ce matériau peut être employé.

Zusammenfassung

Es wurde eine Untersuchung über den Einfluss der folgenden Faktoren auf die Frostbeständigkeit von Beton vorgenommen :

1) Wasserzementfaktor.
2) Zementbeigabe.
3) Kornzusammensetzung.
4) Art der Zuschlagstoffe.
5) Verwendung von Zusatzmitteln.

Die Prüfungen wurden an Betonprobewürfeln von 10,2 cm Kantenlänge durchgeführt, die einem täglichen Wechsel von Gefrieren in der Luft bei $-20°$ C und Auftauen in Wasser von ungefähr 14° C unterworfen waren. Der Schaden durch das periodische Gefrieren und Auftauen wurde an der Verringerung der Druckfestigkeit des Betons und an der Anzahl der Perioden gemessen, die notwendig waren, um eine völlige Zerstörung des Betons herbeizuführen. Die Ergebnisse werden an Hand von Kurvendiagrammen dargestellt, in denen die Druckfestigkeit der Probewürfel einerseits und ihr Alter und die Anzahl der Perioden andererseits aufgetragen wurden. Diese Ergebnisse können für jegliche Art Beton als ein rein zahlenmässiges Verhältnis ausgedrückt werden. Man nennt sie die Beständigkeitswerte (durability factor). Für den Einfluss der Zementbeigabe und der Kornzusammensetzung wird eine Erklärung vorgeschlagen.

Der Vergleich der Laboratoriums- mit den Baustellenprüfungen zeigt deutlich die Genauigkeit der Laboratoriumsprüfungen und die kurze Zeit, in der die Ergebnisse erzielt werden können. Es werden Anregungen bezüglich der Erfordernisse gemacht, die zur Frostbeständigkeit des Betons nötig sind. Die wichtigsten Schlussfolgerungen sind :

a) Die Betonbeständigkeit hängt in erster Linie vom Wasserzementfaktor ab und nimmt mit geringerem Wasserzementfaktor zu.

b) Die Beständigkeit wird durch die Verwendung von Mischungen mit geringem Zement-Zuschlagstoffverhältnis erhöht.

c) Einige Kreide- und Kalksteinzuschlagstoffe ergeben einen Beton, der mit geringem Wasserzementfaktor eine genügende Frostbeständigkeit aufweist.

d) Einige luftzuführende (air-entraining) Zusätze ergeben eine Mischung von verbesserter Beständigkeit und Verarbeitbarkeit. Die Druckfestigkeit wird jedoch dabei gewöhnlich verringert.

Ein besonderer Fall betrifft den Gebrauch von Kreide beim Betonstrassenbau, wobei Versuche über die Anwendbarkeit dieses Materials durchgeführt wurden.

Summary

An investigation has been made to determine the effect of the following factors on the frost-resistance of concrete :

1) water-cement ratio,
2) cement content,
3) aggregate grading,
4) type of aggregate,
5) use of admixtures.

The tests were carried out on 4-in. (10.2 cm) concrete cubes subjected to daily cycles of freezing in air at −20° Centigrade and thawing in water at about 14° Centigrade. The damage done by the freezing cycles was measured by the reduction in the crushing strength of the cubes, and ultimately by the number of cycles required to cause complete disintegration. The results are given by means of a series of graphs showing the crushing strengths of cubes plotted against age and number of freezing cycles. These results for each type of concrete may be expressed by a single number, called the Durability Factor. A suggested explanation is given of the effect of cement content and aggregate grading on the durability of concrete.

The correlation of laboratory tests with field tests emphasises the severity of the laboratory tests and the comparative rapidity with which the results may be obtained. Recommendations are given for the requirements of a concrete to resist damage by frost action. The principal conclusions reached are :

a) The durability of concrete is primarily dependent upon the water-cement ratio, and the lower the water-cement ratio the greater the durability.

b) The durability is improved by the use of mixes having low cement paste-aggregate ratios.

c) Some chalk and limestone aggregates produce a concrete having satisfactory resistance to frost action provided a low water-cement ratio is used in the mix.

d) Some air-entraining admixtures produce a mix having improved durability and workability, but this is generally accompanied by a reduction in crushing strength.

A special case of the effect of aggregate type concerns the use of chalk in cement-grouted road construction and experiments were carried out to determine the conditions under which this material could be used.