Concrete and Masonry Movements

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Preface

In the past, movements of concrete and masonry buildings have been attributed to causes structural failure but these instances have been rare because of good design practice. The latter recognizes that precise knowledge of movements is important in order to achieve the desired design serviceability criteria and avoid costly repairs due to lack of durability. Excessive movements are undesirable and even acceptable movements when restrained can cause undue local material failures, which may be dangerous, unsightly, and expensive to remedy. In some cases such as bridges and high-rise buildings large deflections can cause general alarm even though they may be structurally safe.

"Concrete and masonry movements" is a compilation of knowledge of four basic categories of movement: elasticity, shrinkage, creep and thermal movement but within each category there are several different types. All are explained and discussed in detail from theoretical viewpoints as well as from experimental observations. For concrete, up-to-date literature particularly on the effects of new chemical and mineral admixtures, and recycled waste materials are added to existing knowledge while, for masonry, comprehensive literature reviews, models, and viewpoints are presented. The role played by transfer of moisture at the unit/mortar interface is investigated together with the causes of cryptoflorescence and its effect on creep of masonry. Although the two materials are the oldest construction materials and tend to be treated separately by their respective professional institutions, the approach in this book considers deformations of concrete and masonry side by side or even together since they have many common features that result in similar properties and behaviour. On the other hand, they also have dissimilar features mainly emanating from the use of fired clay units in masonry, which can result in totally different behaviour; those features are highlighted in separate chapters.

This book has been written for undergraduate, postgraduate students and practicing civil engineers who wish to understand why movements occur and how to take them into account when designing concrete and masonry structures. For undergraduate students, underlying principles responsible for each type of movement are given and illustrated by worked examples and problems at the end of each chapter. The postgraduate student requires background knowledge of previous research on appropriate topics before embarking on new approaches, methods, and construction materials, and such background literature is presented for each topic with comprehensive list of references at the end of each chapter. For practicing civil and structural engineers, latest research findings are given together with relevant Codes of Practice prescribed by British, European, and American standards, the application and comparison of which are demonstrated with worked examples.

Acknowledgments

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Particular thanks is given to the University of Leeds for granting permission to reproduce information from several masters and doctorate theses to compile tables and figures: (Figure 5.2; Table 6.1; Figures 8.18, 9.2, 6.21, and 6.22; Tables 10.3 and 10.4; Figure 10.16; 10.21; 12.3; 15.22; 16.7, and 16.9). Similarly, special appreciation is forthcoming to the following organizations for granting permission to use extensive data from numerous publications by the American Concrete Institute (ACI), The International Masonry Society (Stoke-on-Trent, formerly the British Masonry), the Institution of Civil Engineers (ICE) including Thomas Telford Ltd. (London), RILEM (Reunion Internationale des Laboratoires et Experts de Materiaux, Systems de Construction et Ouvrages), Bagneux, France and the British Standards Institution. Details of each publisher and locations in the book are given below:

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Other publishers which are acknowledged for their contributions are now listed. The American Society for Testing and Materials (ASTM): Figure 10.10; Figures 15.18 and 16.25. Institution of Structural Engineers (ISE) including The Structural Engineer: Figures 11.11–11.16; Tables 11.19–11.22 The Concrete Society, including Concrete Journal: Figure 10.3 and Table 13.1. Society of Petroleum Engineers: Figure 10.13. Elsevier including Cement and Concrete Composites, Prentice-Hall: Figures 7.9 and 4.9. Lucideon, formerly CERAM Building Technology, British Ceramic Research Ltd.: Figure 5.6; Table 7.3; Figure 8.2; Figure 8.9; Figure 8.18; and Table 13.7. US National Institute of Standards and Technology: Figure 6.1. Prestressed Concrete Institute: Table 10.6. DIN (German Institute for Standardisation): Figure 10.5. Brick Development Association (BDA Design Note): Figure 14.15. Swedish Cement and Concrete Institute: Table 10.2. Portland Cement Association: Figure 10.7; Figure 15.1; Figure 15.4. CIRIA (Construction Industry Research and Information Association): Table 14.2. US Bureau of Reclamation: Figure 16.9. IHS BRE (The Building Research Establishment): Table 13.6. Pearson Education Ltd (including Prentice-Hall): Figures 2.1–2.4, Figure 2.5; Figure 4.9; Table 8.4; Figure 9.2; Figure 9.6; Figure 12.1; Figure 12.2; and Figure 13.2. Van Nostrand Reinhold (including Chapman and Hall): Figures 14.9 and 16.26. Japan Society of Civil Engineers: Figure 16.10. Japan Cement Association: Figure 15.3. Structural Clay Products: Figure 12.2. John Wiley and Sons: Table 15.2. Hanley Wood Business Media (Concrete Construction Magazine): Figure 6.15.

The author would like to acknowledge contributions made by numerous students who undertook research under the author's supervision, many of which are referenced throughout the book. Also, there is special acknowledgment to Adam Neville with whom the author studied and coauthored research papers and books over many years; his industry and meticulous attention to detail have been an inspiration. The important contributions by laboratory technical staff in teaching practical skills and experimental techniques to research students are not forgotten and so they are also acknowledged, and in particular the author is grateful to Vince Lawton. Lastly, but not least, the unwavering support of my wife Cath, who suggested the writing of this book in the first place, is gratefully acknowledged.

1 Introduction

"Concrete and masonry movements" is a compilation of existing and up-to-date knowledge of movements of two traditional construction materials, based upon the author's research and teachingover a period of 30 years. It is a reference book that brings together theory and engineering practice with worked examples and, consequently, is suitable for the practising engineer, research student, and undergraduate student studying civil engineering.

The presentation is somewhat different because it considers deformation properties of plain concrete and plain masonry together. Structural concrete and masonry containing steel reinforcing bars or prestressing tendons are not included. Conventionally, properties of concrete and masonry have been treated as separate composite materials by their respective professional institutions in spite of having common constituents: cement, sand, and coarse aggregate (brick or block). The theme of the book is to consider each type of movement of concrete and masonry in separate chapters, but to emphasize common features, except where behaviour and features are so common that treatment in different chapters is not warranted. It is the author's belief that the mutual exchange of knowledge in this manner will lead to a greater understanding of the movement properties of both materials.

What is essentially different about the two materials is when the clay brick or block is used as the "coarse aggregate" constituent, because of its behaviour under normal ambient conditions and how it can react with mortar to influence the movement of masonry. The book emphasizes the property of clay brick units exhibiting irreversible moisture expansion, which, under some circumstances, when combined with mortar to build free-standing masonry, can manifest itself as an enlarged moisture expansion due to the occurrence of cryptoflorescence at the brick/bond interface. When occurring in a control wall, this feature appears to increase creep of masonry because of the way in which creep is defined but, in practice, the enlarged moisture expansion is suppressed in masonry provided there is sufficient dead load or external load.

Summaries of all topics discussed are now presented chapter by chapter.

After defining terms and types of movement in Chapter 2, composite models for concrete and masonry are presented for: elasticity, creep, shrinkage or moisture expansion, and thermal movement. A new composite model is developed for masonry. Composite models are useful in understanding how individual components having different properties and quantities interact when combined. The models are applied and verified in other chapters, particularly for masonry, which has the advantage that movement properties of units can be physically measured in the laboratory. With concrete, this approach is not practicable because of the much smaller size of the coarse aggregate, a feature that makes it difficult to measure representative movement characteristics.

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An example of the above-mentioned problem is in Chapter 4, which deals with elasticity of concrete. Modulus of elasticity is related to strength empirically because of the difficulty in measurement of aggregate modulus in order to apply theoretical composite models. Short-term stress–strain behaviour in compression leading to different definitions of modulus of elasticity is described together with Poisson's ratio. Main influencing factors are identified and effects of chemical and mineral admixtures are discussed in detail. Relations prescribed by U.S. and European standards are given for estimating modulus of elasticity from strength in tension as well as corresponding relations in compression, but there is a large scatter mainly because of the failure to quantify the influence of aggregate precisely.

Chapter 5 deals with elasticity of masonry and, besides presenting current empirical relations between modulus of elasticity and strength, composite models are tested and developed for practical application. In the first instance, it is demonstrated that modulus of elasticity of units and mortar may be expressed as functions of their respective strengths so that the composite model for modulus of elasticity of masonry can be expressed in terms of unit and mortar strengths. However, a limitation of the theoretical approach is demonstrated in the case of units laid dry, which causes moisture transfer at the unit/mortar bond during construction. This mainly affects the elastic properties of the bed joint mortar phase. However, this effect can be quantified in terms of the water absorption of the unit, which is thus an additional factor taken into account by the composite prediction model.

The different types of deformation arising from moisture movement that occur in concrete are described in Chapter 6. These range from plastic, autogenous, carbonation, swelling, and drying shrinkage, but emphasis is given to autogenous shrinkage and drying shrinkage especially, in view of the recent developments in the use of high strength concrete made with low water/binder ratios, very fine cementitious material, and chemical admixtures. Influencing factors are identified and quantified, such as the effects of mineral admixtures: fly ash, slag, microsilica, and metakaolin, and the effects of chemical admixtures: plasticizers, superplasticizers, and shrinkage-reducing agents. Methods of determining autogenous shrinkage are described and the latest methods of prediction are presented with worked examples.

The drying shrinkage behaviour of calcium silicate and concrete masonry, and their component units and mortar joints, are the subjects of Chapter 7. After considering influencing factors, the importance of the moisture state of the units at the time of laying is emphasized because of its effect on shrinkage of the bonded unit, mortar, and masonry. A mortar shrinkage-reducing factor is quantified in terms of water absorption and strength of the unit. The geometry of the cross section of masonry, quantified in terms of the ratio of its volume to the drying, exposed surface area, is also shown to be an important factor. The main influencing factors are accommodated in the composite models, which are developed for practical use to estimate shrinkage of calcium silicate and concrete masonry. Methods prescribed by Codes of Practice are also presented and their application is demonstrated with worked examples.

Moisture movement of masonry built from most types of clay units behaves in a different manner to other types of masonry and to concrete due to the property of irreversible expansion of clay units, which begins as soon as newly-made units have cooled after leaving the kiln. The effect is partially restrained when units are bonded with mortar since the mortar joints shrink, but the net effect in masonry depends on the type of clay used to manufacture the unit and the firing temperature. In fact, masonry shrinks in the long-term when constructed from a low, expanding clay brick. In Chapter 8, a detailed review of irreversible moisture expansion of clay units is undertaken before proposing a model to estimate ultimate values from knowing the type of clay and the firing temperature. Laboratory methods of measuring irreversible moisture expansion of clay units are given. It is then demonstrated that prediction of moisture movement of clay brick masonry can be achieved successfully by composite modeling.

The phenomenon of enlarged moisture expansion of clay brickwork is the subject of Chapter 9, which occurs in special circumstances when certain types of clay unit are bonded with mortar to create conditions for the development of cryptoflorescence at the interface of the brick/mortar bond. In many instances, the clay units responsible for the phenomena are of low strength, have high suction rate, and are laid dry. The degree of enlarged expansion also depends on in-plane restraint of the masonry and, hence, can be suppressed by wetting or docking units before laying, and ensuring there is sufficient dead load acting on the masonry. Enlarged moisture expansion is of particular relevance in measuring creep of clay brickwork by using laboratory-sized specimens, and recommended test procedures are suggested. The chapter examines the nature of efflorescence, the influencing factors, and the mechanisms involved.

Chapters 10 and 11, respectively, deal with creep of concrete and standard methods of prediction of creep. Two chapters are allocated because of the number of factors influencing creep, and the numerous methods available to the designer for estimating elasticity, shrinkage, and creep of concrete, especially with the advent of high performance concrete containing mineral and chemical admixtures. Besides creep in compression, Chapter 10 highlights creep under tensile loading and creep under cyclic compression; prediction of creep under both those types of loading is included. Standard methods of estimating creep of concrete from strength, mix composition, and physical conditions are presented in Chapter 11 and their application demonstrated by worked examples. For greater accuracy, estimates by short-term testing are recommended and, finally, a case study is given to illustrate the recommended approach when new or unknown ingredients are used to make concrete.

Creep of masonry is the topic of Chapter 12. Compared with concrete, there has been only a small amount of research, and therefore there are fewer publications dealing with the subject. A brief historical review is given and a data bank of published results is complied. The chapter draws on the experience of knowledge of creep of concrete to develop a practical prediction model for masonry by quantifying creep of mortar and creep of different types of unit in terms of their respective strengths, water absorption of unit, and geometry of masonry. Current European and American Code of Practice guidelines are presented with worked examples. The association of creep with the presence of cryptoflorescence in certain types of clay brick masonry is also investigated.

Thermal movement of both concrete and masonry is considered together in Chapter 13 in terms of practical guidance prescribed in design documents and by composite modeling using thermal expansion coefficients of constituents: aggregate or unit and mortar, and their volumetric proportions. In practical situations, thermal movement and all the other various deformations of concrete or of masonry occur together and are often partially restrained in a complicated manner. The resulting effects, which may result in loss of serviceability due to cracking, are discussed in Chapter 14, together with remedies adopted in structural design to accommodate movements and to avoid cracking. Types and design of movement joints are described in detail and their application is demonstrated with worked examples.

Existing theories of creep and shrinkage of cement-based materials are based on those proposed for concrete. However, since none explain all the experimentally observed behaviour, a different theory is proposed and developed in Chapter 15, which is based on the movement of absorbed and interlayer water within and through the C-S-H pore structure. A key assumption is that the adsorbed water is load-bearing in having a structure and modulus of elasticity greater than that of “free” or normal water. If adsorbed water is removed, stress is transferred from adsorbed water in the pores to the solid gel of the cement paste, thus increasing its deformation. Drying shrinkage may be regarded as an elastic-plus-creep strain due to capillary stress generated by the removal of water. The theory is applied to several test cases of creep previously unexplained by existing theories.

The final Chapter 16 deals with the important subject of testing and measurement of elasticity, creep, and shrinkage of concrete and masonry. Measurement of the other types of movement are discussed in relevant chapters, and Chapter 16 concentrates on uniaxial-compressive and tensile-loading techniques and types of strain measurement with practical guidance for good, experimental practice in the laboratory. Prescribed American and European methods of test for determining creep of concrete are included, there being no equivalent standards for determining creep of masonry. Other prescribed, standard test methods are included in this chapter, which use length comparators for determining, independently of creep, shrinkage of concrete, mortar, and masonry units.

2 Classification of Movements

The types of movement discussed in this book will be briefly explained and defined in this chapter. The types are grouped as follows:

- Shrinkage and swelling, which includes plastic shrinkage, autogenous shrinkage, carbonation shrinkage, and drying shrinkage.
- Irreversible moisture expansion.
- Thermal expansion and contraction.
- Elastic strain and creep.

Whereas the first three groups of movement are determined from measurements using control, load-free specimens, elastic strain and creep are determined from the measurements of the total strain resulting from identical specimens subjected to external load, which is generally compression. The specific types of movement within a group will be defined shortly, after presentation of a general overview.

Concrete and masonry exhibit changes in strain with time, when no external stress is acting, due to the movement of moisture from or to the ambient medium. In the latter case, these changes are mainly due to drying shrinkage (although other types of shrinkage contribute), while swelling or moisture expansion arises from movement of moisture from the ambient medium. Other types of shrinkage that are usually measured with drying shrinkage are autogenous and carbonation. The generic term "shrinkage" is used for normal-strength concrete but, in the case of high-performance (high-strength and low-permeability) concrete, autogenous shrinkage is more significant and is determined separately.

In the past, the phenomenon of creep of concrete has been variously termed flow, plastic flow, plastic yield, plastic deformation, time yield, and time deformation [1]. This arose partly from the concept of the mechanism of the deformation as seen at the time and partly from a lack of agreement on what was still a newly discovered phenomenon. Nowadays, the term "creep" is universally accepted for both concrete and masonry.

When shrinkage and creep occur simultaneously, the common practice is to consider the two phenomena to be additive. The overall increase of strain of a stressed and drying member is therefore assumed to consist of shrinkage (equal in magnitude to that of an unstressed member of the same size and shape) and a change in strain due to stress, i.e., creep. This approach has the merit of simplicity and is suitable for analyses in many practical applications where shrinkage and creep occur together, but the additive definition is not really correct since the effect of shrinkage appears to increase the magnitude of creep. Nevertheless, this approach is followed in this book, since it has been followed by previous investigators and is universally adopted. To understand the phenomena under drying conditions, the extra component of creep is distinguished

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from creep under conditions of no moisture movement to or from the ambient medium. The former extra component is referred to as drying creep while the latter component is referred to as basic creep, as first used by Neville [2] and by Ali and Kesler [3]; thus, under drying conditions, the total creep is the sum of basic and drying creep.

The additive approach also applies to creep and shrinkage of masonry, except in the case of masonry built with clay bricks exhibiting irreversible moisture expansion and prone to cryptoflorescence at the brick/mortar bond. Here, unstressed free-standing masonry undergoes an enlarged expansion, whereas in masonry under compression cryptoflorescence is suppressed. Thus, use of the additive approach to quantify creep leads to a large and false magnitude of creep.

Definition of Terms Used

Shrinkage and Swelling

Shrinkage of concrete and masonry is caused by loss of moisture by evaporation, hydration of cement, and carbonation. The resulting reduction of volume as a fraction of the original volume is the *volumetric strain*, which is equal to three times the linear strain, so that shrinkage can be measured as a linear strain in units of mm per mm, usually expressed as microstrain (10^{-6}). Conversely, *swelling* is an increase in volume when there is continuous storage in water during hydration due to absorption of water by the cement paste; swelling is much smaller than drying shrinkage.

When freshly laid and before setting, mortar and concrete can undergo *plastic shrinkage* due to loss of water from the exposed surface or from suction by the drier layers underneath or adjacent. Plastic shrinkage is minimized by prevention of evaporation immediately after casting. Figure 2.1 illustrates that, from the initial setting of cement, *autogenous shrinkage* takes place due to internal consumption of water by the hydrating cement and there is no external moisture exchange to or from the set mortar or concrete. Autogenous shrinkage is determined using sealed specimens and occurs rapidly during the initial stages of hydration; it is small in normal-strength concrete and masonry mortar but can be very large in very-high-performance concrete made with a low water/cementitious materials ratio, containing chemical and mineral admixtures. When exposed to a dry environment at a later age, t_o, *drying shrinkage* takes place as a result of loss of moisture from the set concrete or mortar, while swelling occurs due to water storage. When reckoned from age t_o, Figure 2.1 shows that *total shrinkage* consists of drying shrinkage plus some autogenous shrinkage and, although the latter's contribution is less, it may still be significant depending on the type of concrete and the age of exposure to drying t_o.

Carbonation shrinkage takes place in surface layers of concrete and masonry mortar due to the reaction of carbon dioxide in the atmosphere with calcium hydroxide of the hardened cement paste in the presence of moisture. It occurs together and is measured with drying shrinkage but generally is much smaller. In normal-strength concrete and mortar, drying shrinkage is between 40% and 70% reversible on immersion of specimens in water after a period of drying, but this applies to first

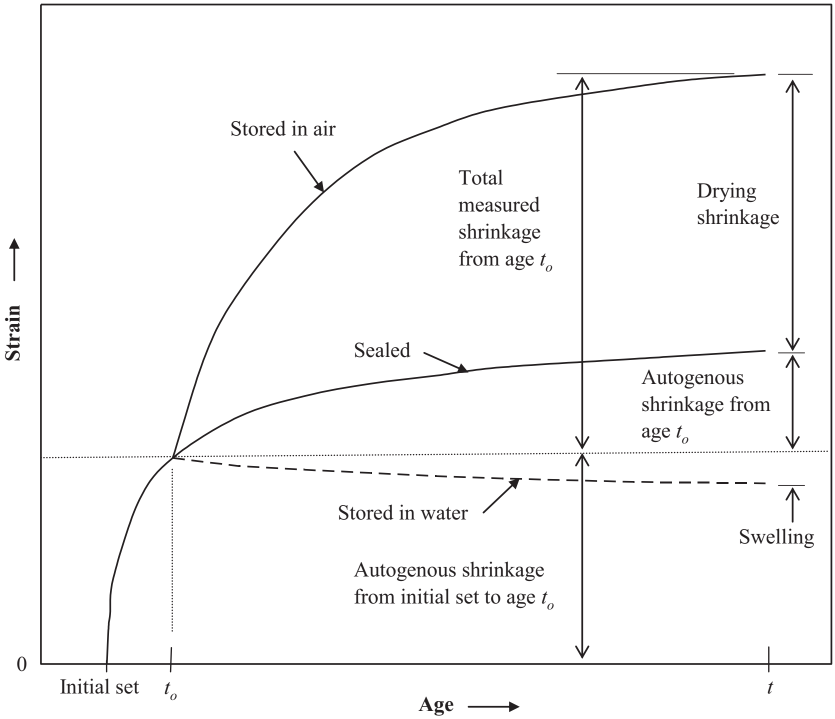

Figure 2.1 Types of shrinkage exhibited by concrete sealed and then stored in different conditions from age t_o.

drying, since subsequent cycles of drying and wetting are almost reversible. On the other hand, autogenous shrinkage and carbonation shrinkage are irreversible. Irreversibility of drying shrinkage is due to pore-blocking by-products of hydration of cement and carbonation during the process of drying.

Irreversible Moisture Expansion

This type of movement is a unique feature of fired clay bricks and blocks, and occurs after the units have cooled after leaving the kiln due to take-up of moisture from the atmosphere; the units expand rapidly at first, then slowly over a long period of time. The effect on clay masonry can also induce irreversible moisture expansion, but at a reduced level, and a net shrinkage is even possible because of opposing restraint by shrinking mortar joints. However, the process depends on type of clay unit and its age. Generally, to minimize irreversible moisture expansion, it is recommended that clay units not be used to construct masonry until they are at least 7 days old and that the design of clay masonry should include movement joints to allow for moisture expansion.

In some types of clay masonry, an *enlarged moisture expansion* may arise due to crystallization of salts at the clay unit/mortar interface, a process known as cryptoflorescence. Enlarged moisture expansion is defined as the expansion in excess of the irreversible moisture expansion of the clay unit used to construct the masonry. The phenomenon typically occurs in small, unrestrained masonry built with units of low strength, high water absorption, and high initial suction rate. On the other hand, enlarged moisture expansion is suppressed in masonry under compression, so that, as stated earlier, it poses a particular problem when determining creep in the laboratory in the traditional way, since the use of small load-free control specimens to allow for moisture movement yields unrealistic high values of creep.

Thermal Expansion and Contraction

Thermal movement arises from thermal expansion or contraction of concrete and masonry elements. Thermal movement is equal to the product of coefficient of thermal expansion and change in temperature and, for both concrete and masonry, the thermal coefficient is assumed to be independent of time.

Elastic Strain and Creep

In the most general form, the elastic strain plus creep–time curve for engineering materials exhibiting time-dependent failure is shown in Figure 2.2, creep being reckoned from the strain resulting from application of load. The strain at zero time is primarily elastic but may include a nonelastic component. Thereafter, there are three stages of creep. In the *primary creep* stage, the rate of creep is initially high and then decreases with time. If a minimum creep rate is exhibited, a *secondary creep* stage (sometimes called *stationary creep*) designates a stage of steady-state creep. The straight line relation of secondary creep may be a convenient approximation when the magnitude of this creep is large compared with primary creep. The *tertiary creep* stage may or may not exist, depending on the level of stress. For instance, in concrete, this may arise from an increase in creep due to growth of microcracks in the cement paste/mortar phase at stress greater than approximately 0.6–0.8 of the short-term strength in compression or in tension. Failure occurs when microcracks link and propagate in an unstable fashion through the whole material, which undergoes large strains prior to disintegration.

For normal levels of stress used in concrete and masonry elements, primary creep cannot be distinguished from secondary creep, and tertiary creep does not exist. The strain–time curve is of the form shown in Figure 2.3 and creep is simply defined as the gradual increase in strain with time for a constant applied stress after accounting for other time-dependent deformations not associated with stress, e.g., shrinkage and thermal movement. Creep may continue, although at a very low rate, for many years.

The strain at loading is classified as mainly an elastic strain and corresponds to the secant modulus of elasticity at the age when the load is applied. For the sake of accuracy, it should be noted that, since both concrete and masonry mature with age, the modulus of elasticity increases with time so that the elastic strain decreases with time under a sustained stress (see Figure 2.4(b)). Thus, strictly speaking, creep should be reckoned as strain in excess of the elastic strain at the time considered and not in

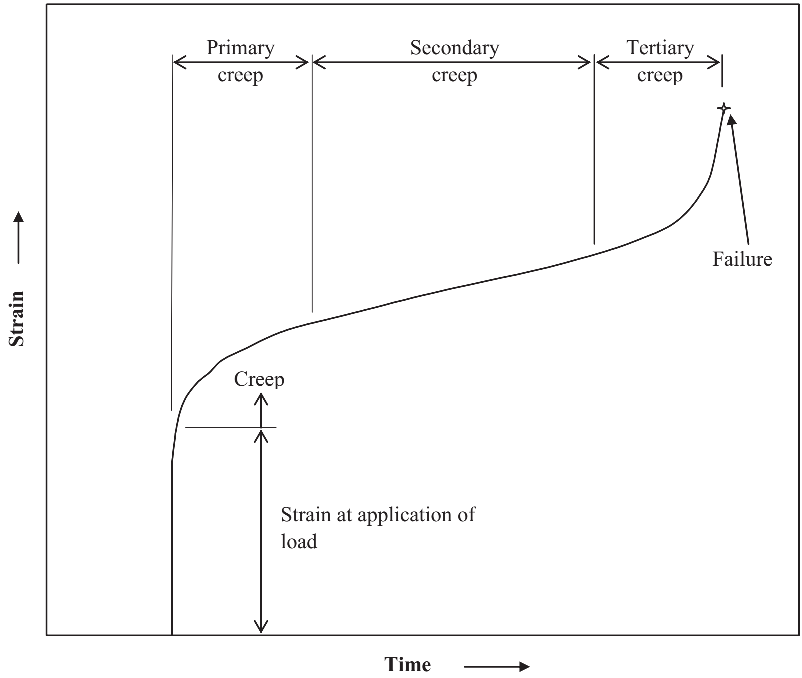

Figure 2.2 General form of the strain–time curve for material undergoing creep leading to failure [1].
Source: Creep of Plain and Structural Concrete, A. M. Neville, W. H. Dilger and J. J. Brooks, Pearson Education Ltd. © A. M. Neville 1983.

excess of the strain at the time of application of load. However, because the difference in the two methods is generally small and because of convenience, the change in elastic strain with age is ignored.

The strain at loading and the secant modulus of elasticity depend on the level of applied stress and its rate of application because the stress–strain curve is nonlinear, as shown in Figure 2.5. In fact, strictly speaking, concrete and masonry are classified as nonlinear and nonelastic materials, pure elasticity being defined as when strains appear and disappear on application and removal of load. For low stresses, the greater initial tangent modulus of elasticity is more appropriate to define the strain at loading of a creep test. If the load is applied extremely rapidly, the recorded strains and nonlinearity are reduced and, correspondingly, the secant modulus of elasticity becomes very similar to the initial tangent modulus. The dependency of instantaneous strain on rate of loading makes the demarcation between elastic and creep strains difficult so that reported test data should include the time taken to apply the load in a creep test, which is generally of the order of 1–2 min, depending on the type of loading apparatus.

The definition of terms is shown in Figure 2.4 using the additive definition of creep discussed earlier for the case when there is concomitant shrinkage. For concrete

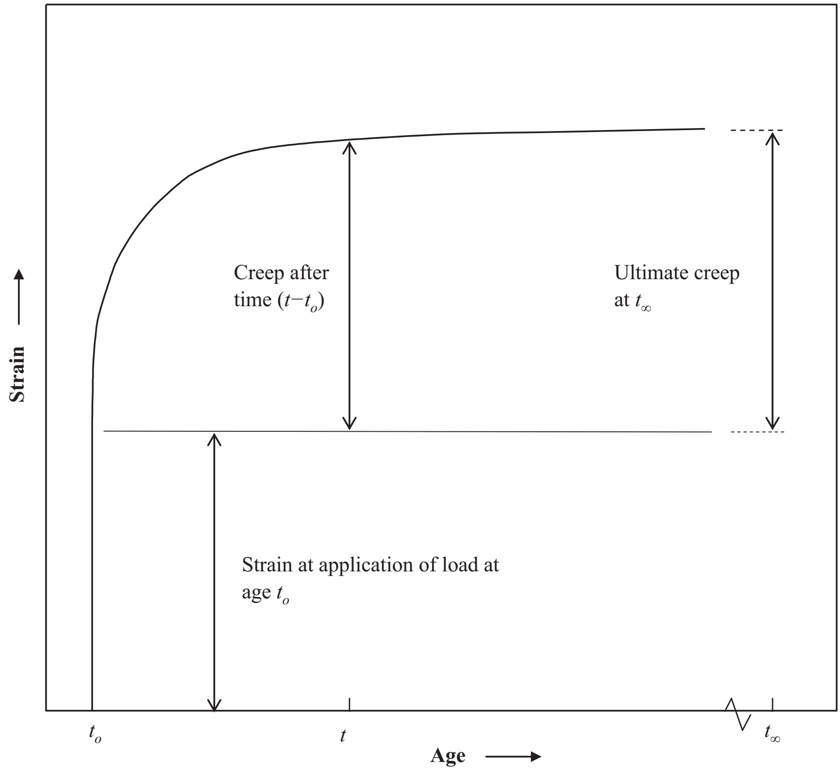

Figure 2.3 General form of the strain–time curve for concrete and masonry subjected to normal levels of sustained stress.

exposed to drying from age to when a compressive load is applied, the shrinkage as measured on a separate load-free specimen is given by Figure 2.4(a) and the total measured strain of the specimen under load is given by Figure 2.4(b) and consists of elastic strain, shrinkage, and *total creep*. For the case of sealed concrete or masonry, the total measured strain of the specimen under load is much less since there is no shrinkage component and creep is smaller, which is, in fact, termed *basic creep* (see Figure 2.4(c)). Thus, the total measured strain of a loaded and drying specimen consists of the components shown in Figure 2.4(d), where total creep comprises basic creep and *drying creep*. Drying creep is the extra creep induced even after allowing for free shrinkage as measured on an unstressed specimen.

It should be noted that basic creep is often used to describe creep of concrete stored in water. In such a case, swelling as measured on a control load-free specimen is usually small compared with creep under a compressive load, so that the conditions approximate to those of no moisture exchange or hygral equilibrium.

Compared with creep at normal temperature, creep is accelerated when heat is applied just before application of load. However, if heated to the same temperature

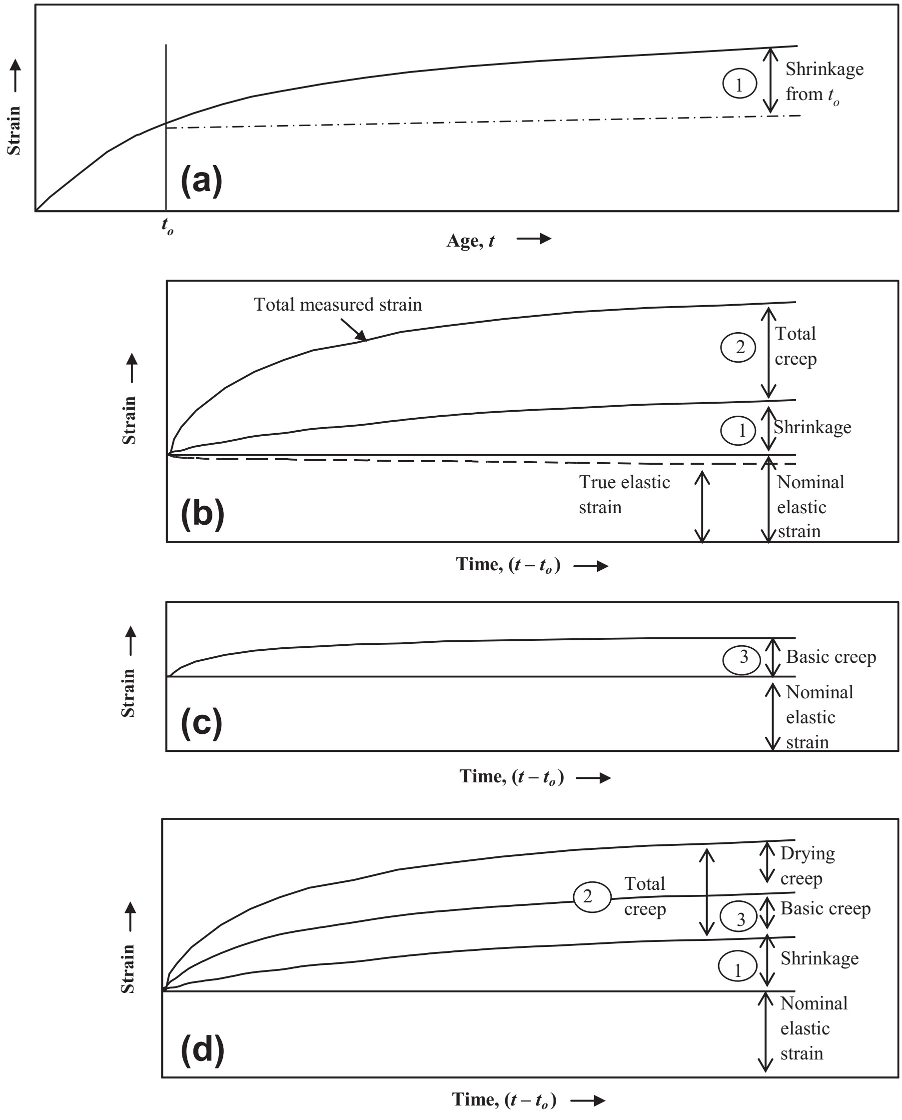

Figure 2.4 Definition of terms used for elastic strain and creep [1]. (a) Shrinkage of a load-free control specimen. (b) Total measured strain of a loaded and drying specimen. (c) Strain of a loaded and sealed specimen. (d) Components of strain of a loaded and drying specimen. *Source*: Creep of Plain and Structural Concrete, A. M. Neville, W. H. Dilger and J. J. Brooks, Pearson Education Ltd. © A. M. Neville 1983.

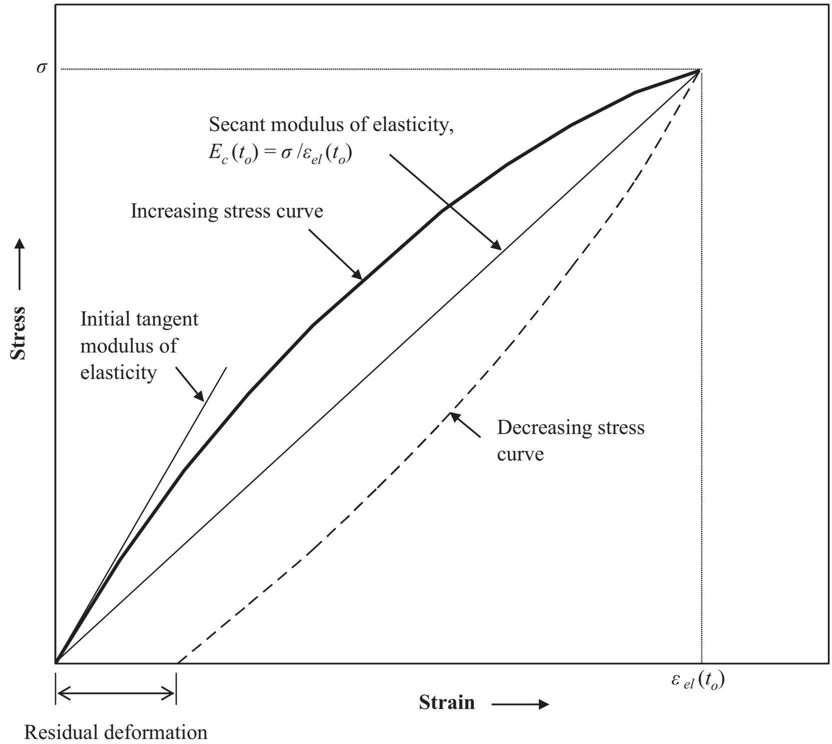

Figure 2.5 Generalized enlarged stress–strain curve for concrete and masonry [1].
Source: Creep of Plain and Structural Concrete, A. M. Neville, W. H. Dilger and J. J. Brooks, Pearson Education Ltd. © A. M. Neville 1983.

just after application of load, an additional component of creep occurs, which is termed *transitional thermal creep* or *transient creep*. At very high temperature, such as in fire, very high elastic and creep strains occur; collectively, these are termed *transient thermal strain*.

Shrinkage, elastic deformation, and creep are expressed as strain, i.e., as dimensionless quantities (mm per mm). However, sometimes it is convenient to give the magnitude of the elastic deformation and creep not for the actual stress applied (usually expressed as a proportion of the short-term strength) but per unit of stress. Such values are called *specific elastic strain* or *elastic compliance*, and *specific creep* or *creep compliance*, which are expressed in units of 10^{-6} per MPa. If $\sigma =$ stress applied, the specific elastic strain (ε_{sp}) is given by:

$$\varepsilon_{sp} = \frac{\varepsilon_{el}(t_o)}{\sigma} = \frac{1}{E(t_o)} \tag{2.1}$$

where $\varepsilon_{el} =$ elastic strain and $E(t_o) =$ modulus of elasticity at age t_o.

Specific creep, c_{sp} or $C(t, t_o)$, is given by:

$$c_{sp} = C(t, t_o) = \frac{c(t, t_o)}{\sigma} \tag{2.2}$$

where $c(t, t_o) =$ creep at age t due to a stress applied at age t_o.

The sum of the specific elastic strain at the time of application of load and the specific creep after time $(t-t_o)$ is termed the *compliance* or *creep function*, $\Phi(t,t_o)$, i.e.,

$$\Phi(t, t_o) = \frac{1}{\sigma}[\varepsilon_{el}(t_o) + c(t, t_o)] = \frac{1}{E(t_o)} + C(t, t_o) \tag{2.3}$$

The ratio of creep to the elastic strain is termed the *creep coefficient*, which is also known as the *creep factor*, viz.:

$$\phi(t, t_o) = \frac{c(t, t_o)}{\varepsilon_{el}(t_o)} = E(t_o) \times C(t, t_o) \tag{2.4}$$

The creep coefficient as defined in Equation (2.4) is the ratio of creep at age t to the elastic strain at the age of loading, t_o. An alternative term is the *28-day creep coefficient*, $\phi_{28}(t,t_o)$, which is defined as the ratio of creep age t measured from loading at age t_o, to the elastic strain at the age of 28 days. The two creep coefficients are related as follows:

$$\phi_{28}(t, t_o) = \phi(t, t_o)\frac{E_{28}}{E(t_o)} \tag{2.5}$$

where $E_{28} =$ modulus of elasticity at the age of 28 days.

A useful parameter in the analysis of modeling of creep effects is to quantify creep in terms of an *effective modulus* of elasticity, which decreases as the time under load increases. The effective modulus is equal to the stress divided by the sum of elastic strain and creep, i.e.,

$$E'(t, t_o) = \frac{\sigma}{\varepsilon_{el}(t_o) + c(t, t_o)} \tag{2.6}$$

where $E'(t,t_o) =$ effective modulus of elasticity at the age of t after load application at the age of t_o.

Hence, specific creep $C(t,t_o)$ is given by:

$$C(t, t_o) = \frac{1}{E'(t, t_o)} - \frac{1}{E(t_o)} \tag{2.7}$$

Creep Recovery

If a sustained load is removed, concrete and masonry undergo an instantaneous recovery followed by a slower time-dependent recovery, known as creep recovery. Figure 2.6 illustrates this situation. Unlike the strain at application of load, the instantaneous recovery is more elastic in nature and is lower in magnitude due to the increase of modulus of elasticity with age. The instantaneous recovery strain is determined by the unloading secant modulus of elasticity of the decreasing stress curve in Figure 2.5 at the age of load removal. Creep recovery rapidly tends to a finite value and is the reversible part of creep that is generally smaller than the preceding creep; the remaining strain is the *residual deformation* or *permanent set* due to *irreversible creep*. In young concrete, creep is large and is only approximately 20% reversible, whereas in mature concrete creep is less but is more reversible.

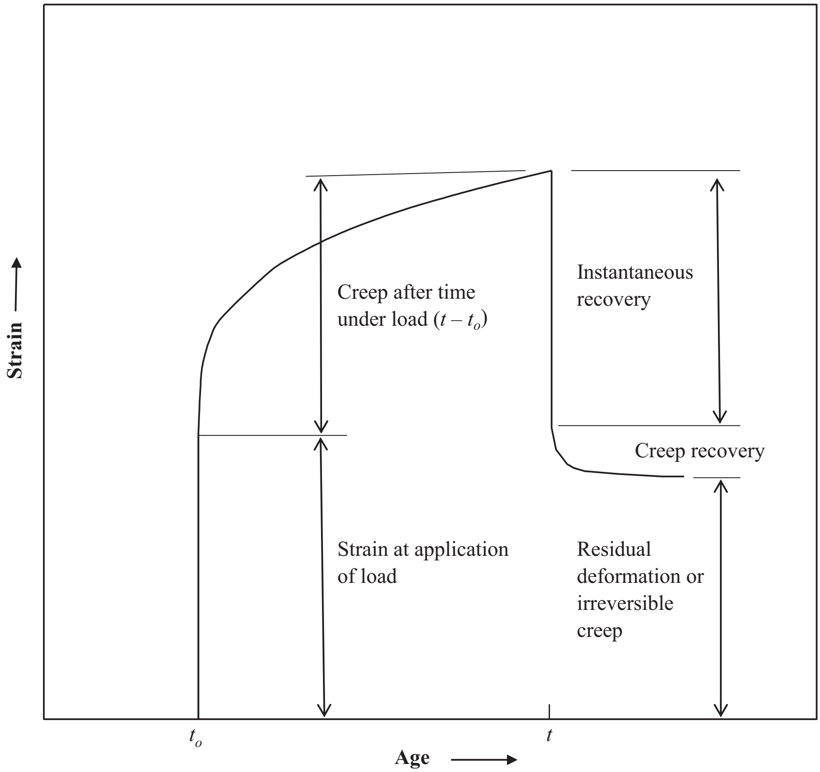

Figure 2.6 Instantaneous and creep recoveries after concrete or masonry has been subjected to load from age t_o and unloaded at age t [1].
Source: Creep of Plain and Structural Concrete, A. M. Neville, W. H. Dilger and J. J. Brooks, Pearson Education Ltd. © A. M. Neville 1983.