



Delayed Elastic Response of Aggregates in Concrete

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ABSTRACT

Concrete's long-term performance under sustained loads is critically influenced by time-dependent deformation, commonly known as creep. Traditional models primarily attribute creep to the viscoelastic behavior of cement paste, considering aggregates as purely elastic materials Which deforms instantly under external load and the deformation remains constant. However, recent research has revealed that the aggregates themselves exhibit a delayed elastic response. This paper provides a comprehensive review of the mechanisms, contributing factors, and engineering implications of the delayed elastic behavior of aggregates in concrete. This work underscores the need to consider the delayed elastic response of aggregates in multi-scale modeling, structural design, and the development of new concrete materials for improved long-term performance.

Keywords:

Aggregate, Creep, Concrete time-dependent deformation, Long-term deformation, Elastic response.



1. Introduction

Concrete is a composite material consisting primarily of cement paste and aggregates, which together define its mechanical and durability properties. Aggregates, which can constitute up to 70-80% of the concrete volume, play a critical role in determining the overall behavior of concrete under load [1-2]. Aggregates are granular materials such as sand, gravel, crushed stone, or recycled concrete particles [3-4]. They are classified into fine aggregates (particles smaller than 4.75 mm) and coarse aggregates (particles larger than 4.75 mm). Aggregates serve several functions in concrete:

1-Volume filler: Aggregates reduce the amount of cement paste required, thereby lowering cost and shrinkage [5-6].

2-Mechanical strength: Aggregates provide compressive strength and stiffness to concrete.

3-Dimensional stability: Aggregates restrain shrinkage and thermal deformation of the cement paste.

4-Durability: Proper aggregates improve resistance to abrasion, freeze-thaw cycles, and chemical attack [3-4].

The mechanical properties of aggregates, especially their elastic modulus, density, and thermal expansion coefficient, significantly influence the overall behavior of concrete. Shrinkage is the reduction in volume of concrete due to moisture loss (drying shrinkage), chemical reactions (chemical shrinkage) or thermal effects. Shrinkage can induce tensile stresses leading to cracking if restrained. Creep in concrete is the gradual increase in strain under sustained stress, that is primarily due to the viscoelastic nature of the hydrated cement paste, which undergoes microstructural rearrangements and viscous flow over time. It affects deflections, prestress losses, and cracking potential in concrete structures [9-13].

Aggregates restrain the deformation of the cement paste, thereby reducing creep and shrinkage strains. The effectiveness of this restraint depends on the stiffness and volume fraction of aggregates. However, the assumption that aggregates behave as purely elastic and instantaneous responders has been challenged by recent studies showing a delayed elastic response [14-17].

Creep is one of the key phenomena influencing the long-term performance of concrete, the time-dependent deformation under sustained load. Thus, it can lead to serviceability issues and structural damage if not properly accounted for.

Traditionally, creep is attributed mainly to the cement paste, as it is the viscoelastic phase of concrete. However, recent research has shown that aggregates also exhibit a delayed elastic response, meaning that their elastic deformation under load is not instantaneous but develops gradually over time. This delayed elastic behavior of aggregates affects the total creep strain of concrete and, consequently, its long-term deformation and durability [18].

In this paper, we highlight the role of aggregates in concrete creep. We offer a comprehensive insight of the delayed elastic response of aggregates in concrete, exploring its mechanisms, influencing factors, experimental evidences, modeling approaches, and engineering implications.

2. Delayed Elastic Response of Aggregates Mechanism

The delayed elastic response refers to the time-dependent elastic deformation of aggregates under load. Unlike an ideal elastic material that deforms instantaneously and recovers immediately upon unloading, aggregates in concrete show a gradual strain increase over time under constant load, followed by a gradual deformation of cement paste in long term loading. Figure 1 highlighted the delayed elastic response of aggregates mechanism.

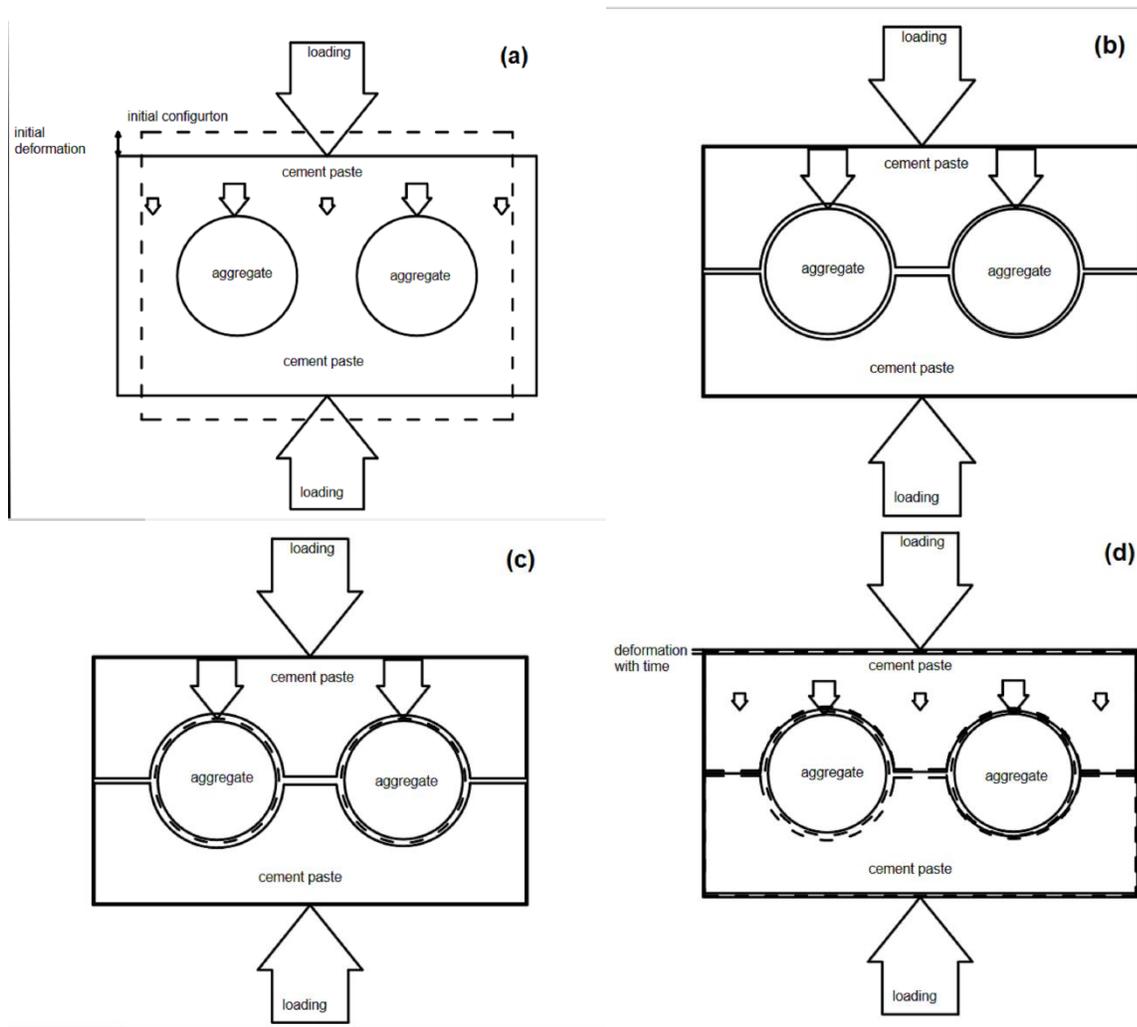


Figure 1. delayed elastic response of aggregates mechanism; (a) load distribution and immediate deformation ; (b) time dependent deformation of cement paste; (c) aggregate elastic deformation under increased loads; (d) load redistribution

The described mechanism illustrates the time-dependent interaction between cement paste and aggregates under sustained compressive loading, highlighting the delayed elastic response of aggregates. This process involves stress redistribution, creep in cement paste, and cyclic load transfer between components:

1a-An axial compressive force When F is applied:

Force portioning: Load distribute between aggregates F_{agg} and cement paste F_{paste} is proportional to the ratio of Elastic modulus (E_{agg}/E_{paste})

$$F_{agg} / F_{paste} = E_{agg} / E_{paste} \quad (1)$$

Instantaneous strain: both component undergoes elastic shortening along the load direction. the strains are equal for both materials



1b- time dependent deformation of cement paste:

Dependent creep moisture of cement paste exhibits viscous flow due to

- 1-Colloidal particle rearrangement [19]
- 2-Capillary water migration [20]
- 3-Microcrack propagation at paste-aggregate interface [21]

-Stress redistribution

As paste creep, it gradually transfer load to aggregates. in this condition, the F_{agg} is increased and F_{paste} is decreased. As the F_{agg} increased, the aggregate elastic deformation is also increased, proportionally.

1c and 1d- aggregate secondary elastic deformation and load redistribution

With increased aggregate loading:

- 1-Aggregates exhibit time-dependent strain from: Delayed elastic response
- 2-mineral constituents Viscoelas [22]
- 3-Interfacial bond adjustments [23]
- 4-The process creates diminishing oscillations: Cyclic relaxation
- 5-Phase: 1 Paste creep → Aggregates take more load
- 6-Phase 2: Paste reloading Aggregate→deformation

Table1. Key Parameters Governing the Mechanism

Factor	Effect on Delayed Response	Source
Aggregate elastic modulus	Higher elastic modulus reduces creep	[1][1]
Paste w/c ratio	Higher ratios increase creep rate	[1][1]
Loading age	Older concrete shows reduced creep	[1][1]
Aggregate size	Larger aggregates improve creep resistance	[1]

This mechanism explains why concrete structures under sustained loads (e.g., bridges, dams) require careful consideration of aggregate properties and paste formulation to control long-term deformations. The cyclic stress redistribution ultimately stabilizes as the system approaches a new equilibrium state with residual stresses [24-30]. Several microstructural mechanisms contribute to this behavior:

- 1-Microcracking and internal friction: Aggregates are not perfectly homogeneous; microcracks and grain boundaries can cause time-dependent deformation.
- 2-Viscoelastic behavior of mineral constituents: Some minerals within aggregates (e.g., mica, clay minerals) exhibit viscoelasticity.
- 3-Moisture movement and pore pressure: Internal moisture redistribution can cause delayed deformation.
- 4-Thermal effects: Temperature gradients can induce delayed strains due to differential expansion. Experimental studies using advanced techniques such as Digital Image Correlation (DIC), Nano indentation, and acoustic emission have confirmed the existence of delayed elastic behavior in aggregates.



3. Influence of Aggregate Properties on Delayed Elastic Response

- Elastic modulus: Aggregates with higher elastic modulus provide greater restraint to creep deformation. For example, granite aggregates (modulus ~70 GPa) reduce creep more effectively than limestone aggregates (modulus ~40 GPa).
- Aggregate size and shape: Coarser aggregates with angular shapes improve mechanical interlock and reduce creep. However, larger aggregates may introduce stress concentrations and microcracking, potentially increasing delayed deformation.
- Mineralogical composition: Aggregates containing clay minerals or micas exhibit higher viscoelasticity, contributing to delayed elastic response. Pure quartz or feldspar aggregates behave more elastically.
- Porosity and water absorption: Highly porous aggregates absorb water, which can redistribute under load and cause delayed deformation. Saturated aggregates may show different delayed elastic behavior than dry aggregates.

Recent advanced models address this by incorporating a delayed elastic component for aggregates through viscoelastic phase modeling using Kelvin-Voigt or Maxwell elements with retardation times. These approaches consider coupled aggregate-paste interactions through load transfer mechanisms and strain compatibility between phases, while finite element simulations integrate microstructural details and heterogeneous material properties. Experimental validations show that models accounting for delayed elastic aggregates achieve better agreement with creep data, particularly in concretes with low paste content or specialized aggregates. The cyclic stress redistribution ultimately stabilizes as the system approaches a new equilibrium state with residual stresses.

4. Engineering Implications and Practical Applications

Selecting aggregates with a high elastic modulus and low viscoelasticity reduces creep and improves durability. Optimizing aggregate gradation enhances packing density and mechanical performance. Reduced creep and shrinkage lead to fewer cracks, improved durability, and longer service life, especially in prestressed and mass concrete structures. Recycled aggregates often have lower stiffness and higher porosity, potentially increasing delayed elastic deformation and creep. Careful characterization and treatment are necessary. Proper curing reduces moisture gradients and microcracking, mitigating delayed elastic effects. Environmental factors such as temperature and humidity influence aggregate behavior [31-43]. The delayed elastic response of aggregates should be considered in Nano and micro-scale characterization, long-term monitoring, multi-scale modeling, and development new materials.

5. Conclusion

The delayed elastic response of aggregates is a critical but often overlooked factor affecting concrete creep and long-term deformation. Understanding this phenomenon requires integrating knowledge of mineralogy, microstructure, and mechanics. Incorporating delayed elastic behavior into models enhances prediction accuracy and informs better mix designs and construction practices. Continued research is essential to fully exploit this knowledge for durable and resilient concrete structures.



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