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Volume change behavior of cement-based repair materials labelled as shrinkage-compensating, shrinkage-compensated or nonshrink

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Abstract. The labels *shrinkage-compensating*, *shrinkage-compensated* and *nonshrink* found in the technical documentation of many proprietary repair materials are all intended in principle to describe systems that exhibit no or little net contraction as a result of shrinkage. In practice, however, these terms are of limited significance in the selection of repair materials without appropriate test data on time-dependent volume changes. This paper provides clarifications on the dimensional behavior of shrinkage-compensating materials and uses experimental findings to emphasize the shortcomings in the information provided in the data sheets of many repair materials labelled as such. In view of a more effective and reliable use of cementitious shrinkage-compensating repair materials, recommendations are made to improve and uniformize the content of the technical data sheets.

1 Introduction

Many proprietary cementitious repair materials are described as *shrinkage-compensating* (*ShC*), *shrinkage-compensated* or *nonshrink*. In most cases, the manufacturer's data sheets do not explain the meaning of such terms. Given the restraint conditions typically provided by the concrete substrate, accurate expansion and shrinkage data are essential for selection of shrinkage-compensating or nonshrink materials that will provide durable repairs. Complementarily to ACI PRC-364.15 TechNote [1], this article provides clarifications on the actual significance of the aforementioned labels and uses experimental findings to emphasize the need for reporting more accurately the information pertaining to shrinkage compensation in the materials data sheets.

2 Shrinkage-compensating systems

Moisture loss is unavoidable in cement-based materials as soon as they are exposed to a relative humidity less than 100%. This moisture loss results in drying shrinkage and volume changes within the material. In addition to shrinkage that occurs due to drying, the hydration reactions will cause some unavoidable chemical shrinkage. Consequently, significant efforts have been made to counteract shrinkage and its undesirable effects, such as tensile stresses and cracking.

Expansive cements were first introduced more than half a century ago to produce so-called shrinkage-compensating concretes. Shrinkage-compensating is

defined by ACI CT [2] as “a characteristic of grout, mortar, or concrete made using an expansive cement in which volume increases after setting and, if properly elastically restrained, induces compressive stresses which are intended to approximately offset the tendency of drying shrinkage to induce tensile stresses.”

In these materials, a chemical agent added to the cement reacts during curing to produce an expansive compound, resulting in a net volume increase of the material. The dosage of expansive agent has to be selected such that the initial expansion will offset subsequent shrinkage, as depicted in Figure 1. More in-depth information on the expansion-shrinkage sequence, the development of tensile stress and the achievement of crack prevention can be found in ACI PRC-223 [3].

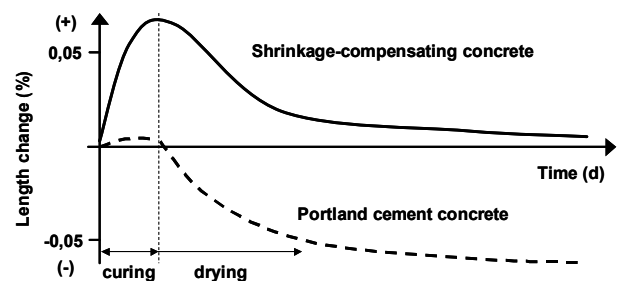


Fig. 1. Comparative length change evolution in ordinary concrete and *ShC* concrete. [3]

The shrinkage-compensation process for repair materials is similar to that for shrinkage-compensating concretes. While expansive cements incorporating calcium sulfoaluminates (CSA) were used for quite some

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time (e.g., ASTM C845 *type K* cement [4]), the industry shifted to the use of expansive components added to the mixture. The main expansive component systems used nowadays to produce *ShC* materials are either CSA-based (*type K*, *type M*), lime-based (CaO – *type G*) or magnesium oxide-based (MgO₂). In addition to the aforementioned agents, other additives such as gas-liberating agents (nitrogen, hydrogen, and oxygen, for example), and diols (dihydric alcohols) are also used. Some dual-action materials even contain two forms of expansive agents; for instance, one agent that produces a gas to counteract shrinkage occurring while the material is still in a plastic state, and another that leads to the formation of a compound that produces expansion in the hardened state. Hence, the various proprietary shrinkage-compensating repair materials available can differ significantly in composition, especially when it comes to the nature of the expansive compound.

The term nonshrink is often, if not always, used in place of the probably more suitable expression shrinkage-compensating. Hydraulic-cement nonshrink grout is defined in ASTM C125 [5] as “a hydraulic-cement grout that produces a volume that, when hardened under stipulated test conditions, is greater than or equal to the original installed volume, often used as a transfer medium between load-bearing members.”

There will be some shrinkage as long as cementitious materials are part of the system; thus, strictly speaking, a cement-based material cannot be non-shrinking. The term is used by many manufacturers, however, to describe the shrinkage-compensating behavior of their materials. It is also used in ASTM C1107 [6] for packaged dry, hydraulic-cement grouts. The important thing to know is that when a prepackaged material is labeled as nonshrink, it means that during the life of the material, under given environmental conditions, the dimensional balance (i.e. expansion minus shrinkage) is supposed to remain positive; there should be no net contraction resulting from drying (Fig. 1). It does not mean that there will be no volume changes.

Because the induced expansion and shrinkage are most generally not synchronous, the effectiveness of a shrinkage-compensating system is dependent on the dimensional balance achievable in given exposure conditions and on the level of restraint during the expansive process to produce a compressive prestress that will decrease with subsequent shrinkage. In new construction, a minimal amount of reinforcement is used to provide this restraint, as recommended in ACI PRC-223 [3]. There is no such provision for repair materials, and it certainly requires some attention, especially in the case of bonded surface repairs without reinforcement where the restraint is provided by simple interface bond with the substrate and, depending on the configuration of the repair (partial-depth versus overlay work), by abutment to the vertical edges. It has been show that when surface preparation is adequate, the chemical prestress can be effectively generated through the interface bond [7].

3 Dimensional balance in *ShC* systems

In the recent years, efforts have been devoted at CRIB-Laval U. to assess and improve the robustness of repair shrinkage-compensating materials prepared with expansive components, notably with respect to the dimensional balance being achieved. A range of variables have been studied, including the type of expansive agent, the rate of addition, the composition and type of binder, the w/cm, and the curing conditions.

In different test programs, the dimensional balance of *ShC* repair concretes was evaluated in both unrestrained and restrained conditions in accordance with modified ASTM C157 [8] and ASTM C878 [9] test procedures. The specimens were demolded at 6 to 8 h after water-cement contact and the initial deformation measurements were performed within minutes. In the typical conditioning sequence, the specimens were then cured until the age of seven days in lime-saturated water at 23 °C for 7 days and then exposed to drying at 23 °C and 50% RH.

The graphs of Figures 2 to 4 present the unrestrained and restrained length change test results for three *ShC* repair concretes prepared with different types of expansive agents. The base concrete mixture was prepared with a CSA type 10 (general use) Portland cement, a 14 mm crushed limestone aggregate and a w/cm of 0.50.

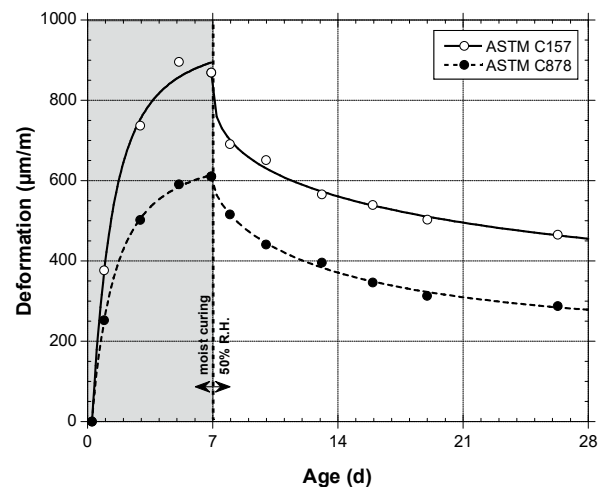


Fig. 2. Comparative free (ASTM C157 mod) and restrained (ASTM C878) length change results of a *ShC* repair concrete mixture prepared with a *type K* component (dosage by weight of binder: 15%; w/cm = 0.50; 14 mm crushed limestone). [10]

It can be noticed that the three types of components being compared yield quite different expansion kinetics and amplitudes, both in free and restrained movement conditions. With *type G*, most of the 7-d expansion (90%) takes place within approximately 24 hours, whereas in the case of mixtures incorporating *type K*-based and MgO₂-based components, it develops much more gradually and, in the present conditions, does not seem to be fully exhausted in neither case at the end of the 7-d curing period. In addition, the subsequent shrinkage recorded from the time the material is exposed at 50% RH varies quite significantly depending on the component. Over a period of 21 days from the onset of

drying, the free shrinkage deformation varies from 150 $\mu\text{m/m}$ in the MgO_2 -based *ShC* mixture to 450 $\mu\text{m/m}$ in the *type K*-based mixture.

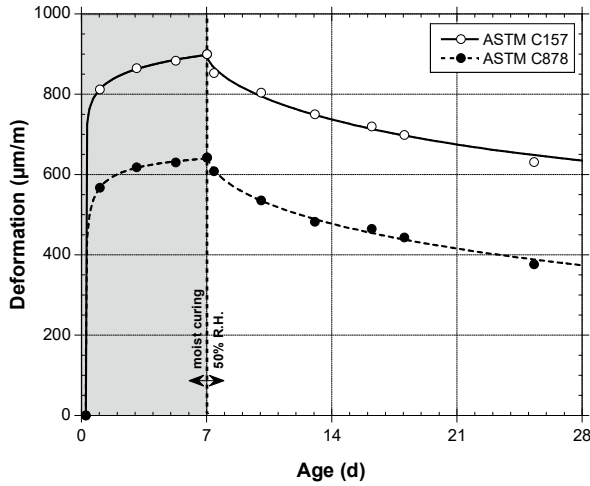


Fig. 3. Comparative free (ASTM C157 mod.) and restrained (ASTM C878) length change results of a *ShC* repair concrete mixture prepared with a *type G* component (dosage by weight of binder: 10%; $w/cm = 0.50$; 14 mm crushed limestone). [10]

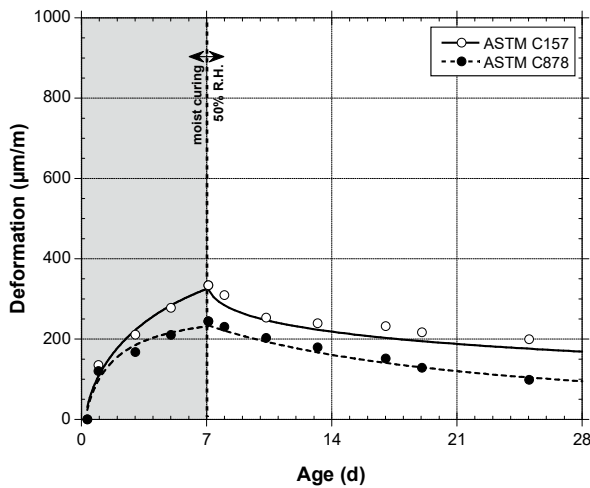


Fig. 4. Comparative free (ASTM C157 mod.) and restrained (ASTM C878) length change results of a *ShC* repair concrete mixture prepared with a MgO_2 -based component (dosage by weight of binder: 7%; $w/cm = 0.50$; 14 mm crushed limestone). [10]

The differences in behavior over time between the three *ShC* repair concrete mixtures can be appreciated further in Table 1, where the free and restrained deformations recorded at the end of moist curing, at 28 days and at 500 days are presented. The data confirm that the nature of the expansive component system influences the free expansion generated, on the free shrinkage, as well as on the dimensional behavior in restrained movement conditions. This highlights the need for more consistent and well defined dimensional characterization.

In the next two figures (Figs. 5-6), the free and restrained deformation results obtained for two *ShC* repair mixtures prepared with *type K* and *type G* expansive components respectively and subjected to two different curing conditions are presented. The base

mixture were similar to those described before, except for the w/cm , which was equal to 0.40. One set of specimens was submitted to curing conditions similar to those of the previous data set (specimens moist cured at 23 °C for 7 days, then exposed at 23 °C / 50% RH) and the other was exposed at 23 °C / 50% RH immediately after demolding. The drastic influence of water curing on the expansive reaction is clearly demonstrated for both expansive systems.

Table 1. Comparative volume change data of a *ShC* repair concrete base mixture ($w/cm = 0.50$; 14 mm crushed limestone) prepared with different components - specimens moist cured for 7 days and then exposed at 50% RH. [10]

Component (% / wgt. of binder)	Average net deformation ($\mu\text{m/m}$)					
	free ASTM C157 mod.			restrained ASTM C878 mod.		
	7 d	28 d	500 d	7 d	28 d	500 d
<i>type K</i> (15%)	+870	+465	+120	+610	+285	-95
<i>type G</i> (10%)	+900	+630	+285	+640	+375	+70
MgO_2 (7%)	+335	+200	-85	+245	+100	-135

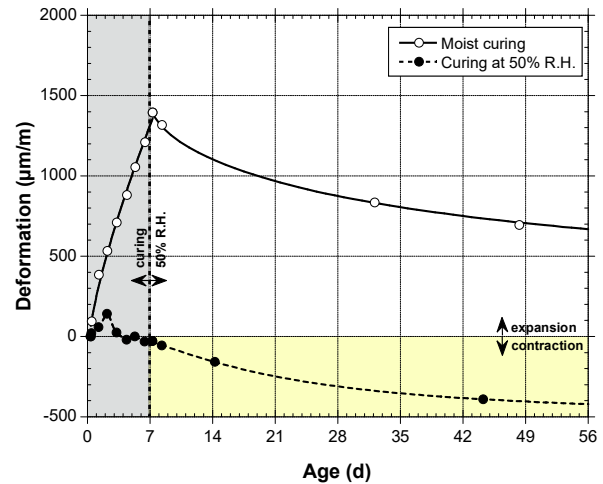


Fig. 5. Influence of curing on the free length change results (ASTM C157 mod.) of a *ShC* repair concrete mixture prepared with a *type K* component (dosage by weight of binder: 16%; $w/cm = 0.40$; 14 mm crushed limestone). [11]

A sustained water supply during the curing period is shown to be more critical for the *type K*-based *ShC* material, as the net expansion generated at 50% RH barely exceeds 100 $\mu\text{m/m}$ and represents less than 10% of the expansion yielded in moist conditions (Fig. 5). In the test specimens exposed at 50% RH, little expansion is recorded during the first couple of days and then the net deformation remains almost stagnant for the next few days, reflecting the competition between the expansion and shrinkage processes. The latter becomes predominant after approximately 5 days, with a likely significant fraction of the expansive potential left

unexploited. As a result, the net deformation balance becomes negative before the end of the curing period.

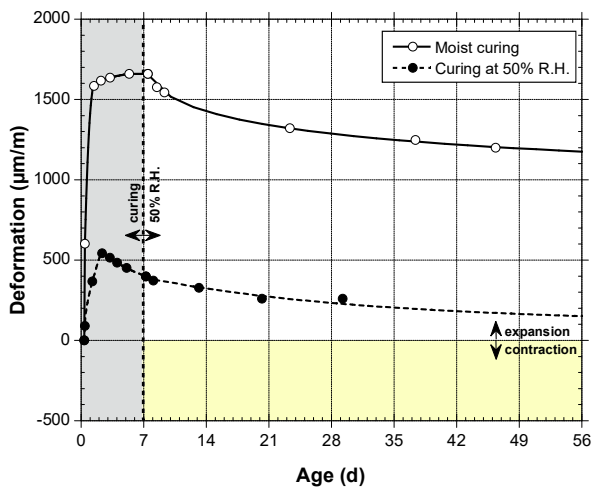


Fig. 6. Influence of curing on the free length change results (ASTM C157 mod.) of a *ShC* repair concrete mixture prepared with a *type G* component (dosage by weight of binder: 8%; $w/cm = 0.40$; 14 mm crushed limestone). [11]

In the *type G*-based mixture, although the magnitude of expansion at 50% RH is three times lower than the value reached in water, the expansion is still significant (Fig. 6). The much faster reaction kinetics of the *type G* expansive component system allows the development of a larger fraction of the total expansion during the first days, despite the water competition available between the hydration of the cement and the *type G* component. Hence, at 56 days, the dimensional balance is still positive (+150 µm/m).

These results demonstrate the strong influence of moist curing and its duration upon the effectiveness of *ShC* systems involving water consumption in the chemical reaction producing expansive compounds. The curing duration affects both the expansion generated and the dimensional balance and, consequently, its influence is more important in systems with a slower rate of reaction.

4 *ShC* and nonshrink repair materials technical data

When consulting the technical information available on repair materials labelled as shrinkage-compensating, shrinkage-compensated or nonshrink, data regarding the dimensional behavior are in many cases insufficiently documented and inadequately characterized. As a result, they are hardly interpretable. This is due, at least in part, to a lack of guidance with respect to the test methods and maximum allowable deformations. In the case of rapid-hardening cementitious materials for concrete repairs, many of which are also claimed to be shrinkage-compensating, ASTM C928 [12] specifies a maximum allowable increase in length change of 0.15% after 28 days in water and the maximum allowable decrease is -0.15% after 28 days in air. However, this range for maximum allowable expansion and contraction is so permissive that most materials fall between the limits.

Moreover, there are no requirements for rate of volume change for rapid-hardening cementitious repair materials. The rate of volume change is important in repairs and is addressed for other types of materials in ASTM C845 [4] and C1107 [6].

As illustrated in the examples of Tables 2 and 3, which are excerpts of actual data sheets of cement-based repair materials downloaded from two different manufacturers' web sites, the information provided with respect to the volume changes and dimensional balance of *ShC* repair systems is often quite confusing.

Table 2. Excerpt from the technical data sheet of an undisclosed commercial repair material – example A. [1]

Description	One component, polymer modified, fast setting, nonshrink repair mortar with fiber and corrosion inhibitor.
Use	Rapid structural and cosmetic repairs to any vertical or overhead concrete; fills holes, spalls, cracks, or honeycombs on vertical or horizontal concrete; restore disintegrated surfaces of old concrete and masonry, cornices, lintels, sills, handrails.
Properties	<ul style="list-style-type: none"> (...) 28-day shrinkage / 50% RH (ASTM C490/C490M): -0.10%. 28-day expansion / 50% RH (ASTM C490/C490M): 0.03%.
Curing	Repaired areas should be kept damp for 20 to 30 minutes or cured with a water-based curing compound.

Table 3. Excerpt from the technical data sheet of an undisclosed commercial repair material – example B. [1]

Description	One-component shrinkage-compensated micro concrete designed for large volume repairs, including structural elements, typically in applications from 2 in. (51 mm) to full depth.
Use	Large volume structural repairs, repair or replacement of spandrel beams, columns, balcony edges, partial or full-depth placements of structural concrete elements, parking garages, water and wastewater tanks, tunnels, dams, bridges, marine structures.
Properties	<ul style="list-style-type: none"> (...) 28-day shrinkage / 50% RH (ASTM C157/C157M): 0.0350%. 21-day shrinkage / 50% RH (ASTM C157/C157M modified): 0.0611%.
Curing	Repair mortar should be cured immediately after the formwork is stripped in accordance with good concrete practices; refer to ACI 308.1.

In Table 2, the listed standard (ASTM C490 [13]) is not a test method itself, but rather a standard practice for the use of the apparatus to determine length change in a variety of ASTM test methods. It is not a sufficient reference for data reporting, as neither the curing time and duration, the demolding time, nor the storage conditions are specified. How can a material be

classified as nonshrink when the reported shrinkage at 28 days is more than three times the reported expansion value at the same age? In addition, how can the same test performed in the same conditions yield at the same age shrinkage in one case and expansion in the other? It can further be noted that there is no reference to the net deformation (dimensional balance) and the suggested moist curing is minimalist.

In the second example (Table 3), without a description of the modification(s) to the ASTM C157 method [8] or proper reference, the reported 21-day shrinkage data is meaningless. Additionally, no expansion data is reported. The curing regimen used in determining the shrinkage data reported is not disclosed and there is absolutely no indication on the level of shrinkage compensation being potentially achieved. Finally, the guidance concerning the curing are very loose.

In addition to the general lack of information regarding the dimensional behavior of shrinkage-compensating repair materials, the discrepancy found in the information contained in data sheets from one manufacturer to the other makes the comparison between different products very difficult. Conformity with either ACI PRC-364.3 [14] or ICRI 320.3R [15] in the preparation of repair material data sheets would contribute to the elimination of these shortcomings.

According to ACI PRC-546.3 [16], when testing shrinkage-compensating materials, it is critical that the demolding time, curing conditions, and comparator reading schedule are understood when interpreting the test results. For example, if the initial measurement is recorded while the material is still expanding, the ultimate drying shrinkage appears less than it actually is; the net length change (expansion less shrinkage) during the test, therefore, should be used as the value for drying shrinkage.

Proper selection and use of such repair materials requires the knowledge of adequately referenced test data on the actual time-dependent volume changes the material undergoes during and after curing. In the technical data sheets, both the length change and restrained expansion data should be determined and reported in accordance with ASTM C157 [8] and ASTM C878 [9] respectively, as modified by the instructions and curing provisions provided in the latest versions of ACI PRC-364.3 [14] and ICRI 320.3R [15]. The use of the ASTM C878 restrained expansion provides information intended to better reflect the dimensional behavior of the material in the structure. The modification proposed in ACI PRC-364.3 and ICRI 320.3R allows to exploit the procedure in the drying phase as well.

In practice, without adequately referenced test data on the actual time-dependent volume changes the material undergoes during and after curing, the designations shrinkage-compensating, shrinkage-compensated and nonshrink are of limited significance in the selection of repair materials. In the absence of appropriate information, the specifier should consult the manufacturer to determine the suitability of a given material in a given situation.

5 Conclusion

All cementitious materials undergo some drying shrinkage when exposed in an environment where relative humidity is below 100%. The labels shrinkage-compensating, shrinkage-compensated and nonshrink found in the technical data sheet of many prepackaged repair materials mean in principle that they are formulated to exhibit no or little net contraction upon drying, owing to a chemical expansion process taking place in the early stages of curing. Proper selection and use of such repair materials requires the knowledge of adequately referenced test data on the actual time-dependent volume changes the material undergoes during curing and once it is exposed to drying.

In view of a more effective and reliable use of cementitious *ShC* repair materials, the following recommendations would contribute to resolve the shortcomings highlighted in this paper and improve and uniformize the technical data sheet content:

1. For any repair material relying on shrinkage compensation with the use of an expansive component, the label “shrinkage-compensating” proposed in ACI CT should be used and misleading terms such as “nonshrink” should be avoided;
2. When stating that a material is shrinkage-compensating, it should be indicated to what degree (e.g., zero net contraction, low shrinkage) and under what general conditions (curing, environmental exposure, restraint);
3. For any *ShC* repair material relying on a water-dependent expansive component system, comprehensive guidance should be provided on the curing operations and their influence on the resulting effectiveness of the system to counteract shrinkage and prevent cracking;
4. The reported volume change data should systematically include both the length change and restrained expansion data determined in accordance with ASTM C157 [8] and ASTM C878 [9] respectively, as modified by the instructions and curing provisions provided in the latest versions of ACI PRC-364.3 [14] and ICRI 320.3R [15].

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