Abstract: This study experimentally investigated the dimensional stability of SBR (styrene butadiene rubber)-modified cementitious mixtures in order to determine whether their properties are sustainable as a 3D additive construction material. Dimensional stability refers to resistance to material deformation caused by changes in internal relative humidity and temperature. Hence, drying and thermal shrinkage, which are the primary factors affecting dimensional stability, were tested. The mixing ratio of SBR-modified cementitious mixtures was determined based on a predetermined optimal flow of 70% ± 1% applicable for 3D additive construction applications. The results of this study showed that the elastic modulus, and drying shrinkage strain, excluding the coefficient of thermal expansion, all significantly improved as the SBR/cement ratio increased. In particular, drying shrinkage can be a disadvantage in 3D additive construction because drying in the printed mixtures is rapid due to the large specific exposure area of moldless construction. Consequently, mitigating drying shrinkage is very important. The elastic modulus, drying shrinkage, and coefficient of thermal expansion were all found to be associated with the dimensional stability obtained in this study. It was concluded that using SBR-modified cementitious mixtures was advantageous in terms of dimensional stability.

Keywords: 3D additive construction; SBR-modified cementitious mixtures; dimensional stability; modulus of elasticity; drying shrinkage; coefficient of thermal expansion

1. Introduction

The construction industry faces a number of problems, including declining labor efficiency, increased onsite accident rates, degraded labor quality, site management difficulties, and a reduced skilled labor force [1]. Increased automation is one solution to these problems. Automation has been rapidly advancing in the manufacturing sector, but the propagation of automation technologies in the construction industry has been slow. This slow pace is due to the fact that construction projects are generally large in scale and construction equipment is costly, among other issues [2]. One representative automated technology in the construction industry is 3D additive construction (3DAC). This construction method builds concrete structures by stacking or layering cementitious mixtures. This 3DAC process is operated via computer control. The specified concrete structure is built without a formwork by adding layer upon layer of a cementitious mixture [3]. Most 3DAC technologies currently in use employ cementitious mixtures extruded through a nozzle installed on a gantry system or robotic arm.
This construction method offers several advantages, such as reduced construction costs, accident rates, and construction time; decreased environmental contamination; and the convenient construction of complex structures \[4\]. Consequently, this method is considered a next-generation sustainable construction technology. This 3DAC technology has recently been employed to construct regular buildings, pedestrian bridges, and army barracks \[5–8\]. In such onsite applications, printing materials are considered one of the three core elements, in addition to printing machinery and 3D modeling software. Until now, ordinary Portland cement has typically been employed as the base material, along with various mineral admixtures such as silica fume and fly ash. SBR-modified cementitious mixtures exhibit excellent tensile and flexural strengths and adhesiveness, and favorable levels of resistance to water, abrasion, and chemicals (as compared to ordinary Portland cement) \[9–11\]. However, research on the use of SBR-modified cementitious mixtures in 3DAC is lacking. Therefore, this study experimentally investigated the dimensional stability of SBR-modified cementitious mixtures in order to determine whether its properties are sustainable if used as a 3DAC material.

2. Research Objectives

Dimensional stability is defined as “the degree to which a material maintains its original dimensions when subjected to changes in temperature and internal relative humidity” \[12\]. When freshly hardened concrete is exposed to ambient temperature and humidity, it generally undergoes thermal and drying shrinkage. The stresses produced by such changes in environmental factors can be determined when the modulus of elasticity, relaxation characteristics, and degree of restraint of the material is known. The occurrence of cracks can be determined when the magnitude of this stress is understood. Theoretically, cracks occur when the stress due to temperature changes \(\sigma_t = E \times \alpha \times \Delta T\), where \(\sigma_t\): tensile stress, \(\alpha\): the coefficient of thermal expansion, \(E\): elastic modulus, and \(\Delta T\): temperature change) or relative humidity changes \(\sigma_t = E \times \varepsilon\), where \(\varepsilon\): drying shrinkage strain and \(E\): elastic modulus) exceed the tensile strength of the cementitious mixture, assuming that the material is completely elastic. Factors important when analyzing deformation characteristics include the elastic modulus and drying and thermal shrinkage.

Since 3DAC is a stacking or layering construction method that differs from the more historically common formwork-based construction process, specific material properties are required to be employed in 3DAC. In particular, the properties of fresh printing materials are completely different; they can only be utilized for 3DAC when the four conditions of flowability, extrudability, buildability, and open time are met. Thus, the optimal flow of SBR-modified cementitious mixtures (70% ± 1%) to apply 3DAC was determined by Kim et. al. \[13\]. However, we still do not know yet whether the mixtures that can be utilized for 3DAC are stable enough to maintain their original dimensions after the mixtures have been printed (i.e., it is exposed to ambient temperature and humidity). Hence, the novelty of this research is to determine whether the original dimensions of the SBR-modified cementitious mixtures printed through the 3DAC process are maintained when the temperature and humidity are changed. Therefore, the objective of this study was to experimentally investigate the elastic modulus, drying shrinkage strain, and coefficient of thermal expansion. These are important factors in determining the dimensional stability of SBR-modified cementitious mixtures, a component produced by applying the mixing ratio identified after consideration of the above four requirements.

3. Materials and Specimen Preparation

3.1. Materials

The materials used in this study were ordinary Portland cement, SBR latex, silica sand, fly ash, silica fume, a superplasticizer, and a viscosity modifying agent. The properties of these materials are shown Tables 1–7.
Table 1. Properties of ordinary Portland cement.

| Density (g/cm³) | Chemical Composition (%) | Specific Surface (cm²/g) |
|----------------|--------------------------|-------------------------|
| 3.14           | 2.91                     | 2.41                    |
|                | 2.16                     | 3630                    |

Table 2. Properties of SBR latex.

| Total Solids (%) | pH     | Viscosity (mPa·s) | Surface Tension (dynes/cm) | Specific Gravity (20°C) | Minimum Film-Forming Temp. (°C) |
|------------------|--------|-------------------|-----------------------------|-------------------------|---------------------------------|
| 47–50            | 9.9–10.5 | 40                | 30–35                       | 1.01 ± 0.01             | <4                              |

Table 3. Properties of silica sand.

| Size (mm) | Apparent Density | Purity (%) | Water Content (%) |
|------------|------------------|------------|-------------------|
| 0.08       | 1.57             | 97.3       | <0.1              |

Table 4. Properties of fly ash.

| Density (g/cm³) | SiO₂ (%) | Loss Ignition (%) | Specific Surface (cm²/g) |
|-----------------|----------|-------------------|-------------------------|
| 2.22            | 51.9     | 3.2               | 3651                    |

Table 5. Properties of silica fume.

| SiO₂ (%) | H₂O (%) | Loss on Ignition (%) | Bulk Density-Undensified (kg/m³) | Bulk Density-Densified (kg/m³) | Specific Surface (cm²/g) |
|----------|---------|----------------------|----------------------------------|-------------------------------|-------------------------|
| 96.7     | <1.0    | <3.0                 | 200–350                          | 600–700                       | 157,700                 |

Table 6. Properties of superplasticizer.

| Specific Gravity (20°C) | pH          | Alkali Content (kg/m³) | Chloride Content (kg/m³) |
|-------------------------|-------------|------------------------|--------------------------|
| 1.05 ± 0.05             | 5.0 ± 2.0   | 0.03                   | 0.03 × 10⁻³              |

Table 7. Properties of viscosity modifying agent.

| Appearance | pH (Solution) | Bulk Density (kg/m³) | Moisture Content (%) | Particle Size (0.074 mm, %) |
|------------|---------------|----------------------|----------------------|------------------------------|
| White powder | 8.0–10.0      | 430                   | ≤12                  | ≥95                          |

3.2. Mixture Proportions

Among the many constituents used in this study, the mixture proportions of materials other than SBR were determined through the process of trial and error. SBR latex was added according to the SBR/cement ratios (i.e., 0, 0.05, 0.10, 0.15, and 0.20). The amount of water used was determined based on a water/cement ratio that could maintain a flow of 70% ± 1% for each mixture because the flow of 70% ± 1% was determined by Kim et al. [13] as the optimal flow of SBR-modified cementitious mixtures to apply 3DAC. Table 8 shows the mixture proportions identified for these conditions.
Table 8. Mixture proportions of SBR-modified cementitious mixtures (unit: kg/m³).

| SBR | Cement | Water | Silica | Sand | Fly Ash | Silica Fume | Super-Plasticizer | Viscosity | Modifying Agent |
|-----|--------|-------|--------|------|---------|-------------|------------------|-----------|-----------------|
| 0   | 642    | 289   | 1377   | 184  | 92      | 6           | 0.3              |           |                 |
| 32  | 638    | 271   | 1368   | 182  | 91      | 6           | 0.3              |           |                 |
| 63  | 635    | 254   | 1360   | 181  | 91      | 6           | 0.3              |           |                 |
| 95  | 631    | 236   | 1351   | 180  | 90      | 6           | 0.3              |           |                 |
| 125 | 627    | 219   | 1343   | 179  | 90      | 6           | 0.3              |           |                 |

The flow of 70% ± 1% is optimal, as determined through experiments regarding the four properties of the fresh SBR-modified cementitious mixtures required for 3DAC: flowability, extrudability, buildability, and open time. It is of note that the optimal flow of 70% ± 1% is quite small considering the standard flow of 110% ± 5% defined in ASTM C109/C109M-02: Testing Method for Compressive Strength of Hydraulic Cement Mortar [14], used when producing cementitious mortar specimens for compressive strength testing.

3.3. Specimen Production

To produce the test specimens, the mixture flow was changed from 110% ± 5% to 70% ± 1%. This change was made to ensure the optimal flow for 3DAC applications. For the elastic modulus and drying shrinkage tests, ø50 mm × 100 mm cylindrical specimens and 70 mm × 70 mm × 320 mm prismatic specimens were produced, respectively. The prismatic specimens for the thermal expansion coefficient test were produced with the same dimensions as the test specimens for the drying shrinkage test.

Of the above-detailed test specimens, those for compressive strength, flexural strength, elastic modulus, and thermal expansion coefficient were used after curing for 28 days in an environmental chamber controlled at 23 °C ± 2 °C and 65% ± 5% relative humidity. The drying shrinkage test was carried out immediately after the samples were demolded from the mold.

4. Testing Method

4.1. Modulus of Elasticity

The modulus of elasticity represents the stress–strain relationship of a material. Hence, the elastic modulus was tested according to ASTM C469/C469M–14: Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression [15]. The test equipment used was a 25-ton UTM (INSTRON 8502) and a data logger (Tokyo Sokki, TDS-602). Electrical resistance strain gauges were employed to measure the instantaneous strain. The change in temperature around the specimen should not be exceeded by more than 2 °C during the test. Figure 1 shows the test setup.

Figure 1. Test setup for determining the modulus of elasticity.
4.2. Drying Shrinkage

ASTM C596-01: Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement [16] was applied for drying shrinkage test. The test was carried out in an environmental chamber controlled at 23 °C ± 2 °C and 60% ± 5% relative humidity. The drying shrinkage strain was measured via an embedment-type strain gauge. A data logger (Tokyo Sokki, TDS-602) was used for data collections. This approach is simpler and more accurate than reading a length comparator. To facilitate the symmetric drying condition, all the specimens were demolded after 24 h of curing. Drying shrinkage was measured for up to 28 days. Figure 2 shows the test setup, along with the specimens cast in molds.

![Figure 2. Test setup for measuring drying shrinkage and specimens cast in molds.](image)

4.3. Coefficient of Thermal Expansion

ASTM C531-18 (Linear Shrinkage and Coefficient of Thermal Expansion of Chemical-Resistance Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes) [17] was applied to determine the coefficient of thermal expansion. The thermal strain was measured using an embedment-type strain gauge and a data logger (Tokyo Sokki, TDS-602). Measuring strain using strain gauge is much more convenient than measuring strain using length comparator. After thermal stabilization for 5 h at 25 °C, the temperature was increased to 80 °C, and the corresponding strain was measured. Thermal calibration was performed to determine the true thermal strain. Figure 3 shows the test setup.

![Figure 3. Test setup for measuring thermal expansion.](image)

5. Results and Discussion

5.1. Modulus of Elasticity

According to Hooke’s law, in linear elastic materials, the elastic modulus is constant regardless of the stress [18]. Strictly speaking, the elastic modulus is only applicable to the linear elastic section of...
the stress–strain curve. Therefore, the secant modulus of elasticity is used for materials like concrete, which do not have a clearly linear elastic section of the stress–strain curve. Although the chord and tangent moduli of elasticity exist, they are not used [19].

While the stress–strain relationship for concrete is nonlinear, it can be considered the linear elastic section of small stress ranges (approximately 40% to 50% of the ultimate stress); this is also the allowable stress range. Thus, concrete can be considered an elastic material within the allowable stress range. The stress–strain diagrams obtained in this study are shown in Figure 4. According to Figure 4, the obtained compressive strengths (ultimate stresses) were 50.9 MPa, 54.3 MPa, 58.0 MPa, 60.4 MPa, and 63.5 MPa, respectively when the SBR/cement ratios were 0, 0.05, 0.10, 0.15, and 0.20. The secant modulus of elasticity was determined using the slope of the line connecting the origin and a point corresponding to 40% of the ultimate stress. The values for the secant modulus of elasticity that were obtained for the SBR/cement ratios of 0, 0.05, 0.10, 0.15, and 0.20 were 21.6 GPa, 22.9 GPa, 23.1 GPa, 24.4 GPa, and 25.3 GPa, respectively. These values increased as the SBR/cement ratio increased, as can be observed in Figure 5. Additionally, Figure 6, which shows the relationship between the compressive strength and elastic modulus, reveals that the elastic modulus increased as the compressive strength increased. The relationship between the compressive strength and elastic modulus showed a strong correlation with a coefficient of determination (R²) of 0.9508.

Figure 4. Stress–strain diagrams for different SBR/cement ratios.

Figure 5. Moduli of elasticity for different SBR/cement ratios.
In a previous study, Ohama et al. [9] reported elastic modulus values for SBR-modified concrete of 20.0 GPa, 22.0 GPa, 24.0 GPa, 24.0 GPa, and 20.0 GPa for SBR/cement ratios of 0, 0.05, 0.10, 0.15, and 0.20, respectively. These values were slightly lower than the results obtained in this study. The difference is thought to be due to the low compressive strength, since silica fume was not used. The maximum compressive strains obtained from the stress–strain curves according to the associated SBR/cement ratios are shown in Figure 7. The maximum compressive strains for the SBR/cement ratios of 0, 0.05, 0.10, 0.15, and 0.20 were $2800 \times 10^{-6}, 3200 \times 10^{-6}, 3400 \times 10^{-6}, 3500 \times 10^{-6}$, and $3800 \times 10^{-6}$, respectively. It was found that the maximum compressive strain increased as the SBR/cement ratio increased.

However, although this result showed the same trend as the result reported in Shiroishida [20], where the maximum compressive strain during failure increased as the polymer/cement ratio increased and the maximum compressive deformation increased by two to three times for a polymer/cement ratio of 0.20 (as compared to when no polymer was used), the margin of increase was small.
5.2. Drying Shrinkage

Drying shrinkage is a major cause of cracks. When cementitious mixtures come into contact with ambient air, drying begins and the dried exterior contracts. Thus, shrinkage stress occurs on the exterior surface and cracks ensue when this stress exceeds the tensile strength of the cementitious mixture. Important parameters that impact drying shrinkage include the aggregate content, stiffness, water content, cement content, time of exposure, relative humidity, and size and shape of the concrete member [19]. Also, among the admixtures, pozzolanic materials (except for the AE agent, hardening accelerator, and fly ash) also increase the drying shrinkage.

The thin cracks that initially occur on the surface due to drying shrinkage become deeper as time passes. This drying shrinkage can be reduced by increasing the amount of coarse aggregate in the mix of concrete and decreasing the unit water content [21]. Figure 8 shows the results of the shrinkage test obtained from this study. Figure 8a shows the hourly variation over 24 hours and Figure 8b indicates the daily variation over 28 days. It can be observed that the shrinkage dramatically increased between 5 and 10 hours of curing.

![Figure 8](image_url)

Figure 8. Drying shrinkage strain comparisons for different SBR/cement ratios at (a) curing age: 24 hours and at (b) curing age: 28 days.

Figure 9 shows the drying shrinkage developments for the first of 28 days, according to the SBR/cement ratio. These results show that the drying shrinkage for the SBR/cement ratios of 0, 0.05, 0.10, 0.15, and 0.20 were $331 \times 10^{-6}$, $282 \times 10^{-6}$, $225 \times 10^{-6}$, $184 \times 10^{-6}$, and $144 \times 10^{-6}$, respectively. A decreasing trend was observed in drying shrinkage as the SBR/cement ratio increased. Generally, the drying shrinkage of cementitious mixtures varies depending on the aggregate/cement and water/cement ratios, but generally ranges between $200 \times 10^{-6}$ to $1200 \times 10^{-6}$ [22].
Polymer-modified concrete exhibits lower drying shrinkage compared to that of ordinary Portland concrete because of the high-water retention of polymer-modified concrete, and preventing moisture evaporation by blocking pores. Moreover, Kawano [28] reported that compared to ordinary Portland concrete, the reduction in the drying shrinkage of latex-modified mortar is mainly due to the effects of the surfactants and antifoamers contained in latex. Kardon [29] explained that the polymer-modified concrete exhibits lower drying shrinkage compared to that of ordinary Portland concrete because of the high-water retention of polymer-modified concrete, and its high tensile strength improves extensibility, reducing cracks caused by drying shrinkage. Similarly, it was found that the drying shrinkage of polymer-modified cementitious mixtures can be reduced through various factors.

Active methods of further reducing drying shrinkage include adding expansive additives during the mixing of cementitious mixtures and by adding ethylene during polymer formulation [30]. However, the drying shrinkage of cementitious mixtures is small, and because there are a variety of methods for reducing drying shrinkage, 3DAC applications make this aspect significantly advantageous. Since 3DAC does not use a formwork, the barrier between the concrete and surrounding environment is essentially removed and the exposed surface areas of printed structures are much larger than those of cast structures. Also, the possibility of crack formation from autogenous shrinkage becomes greater because the water/cement ratio used in 3DAC cementitious mixtures is low. Thus, the mix design must minimize dimensional changes due to drying and autogenous shrinkage. Considering the argument that greater attention should be paid during the curing process [3], reducing drying shrinkage with the addition of SBR latex could offer a significant advantage to construction using 3DAC.

5.3. Thermal Expansion

Thermal expansion occurs when the internal and external temperatures of a cementitious mixture rise. There are two factors that cause temperature changes: cement hydration and temperature change.
These factors cause the volume to change. Cracks occur when the stress generated by the strain of such a volume change exceeds the allowable tensile stress of the cementitious mixture. Thermal shrinkage is very important for massive concrete elements. When the internal temperature rises due to hydration heat, a significant temperature difference is generated between the concrete surface and the part deep within. Here, tensile stress is generated by shrinkage at the lower-temperature concrete’s surface, resulting in cracks. Its magnitude can be controlled by controlling the coefficient of thermal expansion of the aggregate cement content and type, as well as the temperatures of the materials used to make the concrete [19].

Thermal expansion can be divided into linear thermal expansion and volumetric thermal expansion. The magnitude of the thermal expansion varies based on the crystalline structure and atomic arrangement of the material. This study investigated linear thermal expansion. Figure 10 shows the thermal strain measurement results according to the SBR/cement ratio. The thermal strains were $437 \times 10^{-6}$, $513 \times 10^{-6}$, $570 \times 10^{-6}$, $774 \times 10^{-6}$, and $914 \times 10^{-6}$ for the SBR/cement ratios of 0, 0.05, 0.10, 0.15, and 0.20, respectively. The results reveal an increasing trend in thermal strain as the SBR/cement ratio increased.

![Thermal Strain Diagram](image)

**Figure 10.** Thermal strains for different SBR/cement ratios.

Figure 11 shows the test results of the linear thermal expansion coefficients, which were $5.8 \times 10^{-6}/^\circ\text{C}$, $6.8 \times 10^{-6}/^\circ\text{C}$, $7.5 \times 10^{-6}/^\circ\text{C}$, $10.1 \times 10^{-6}/^\circ\text{C}$, and $12.2 \times 10^{-6}/^\circ\text{C}$ for the SBR/cement ratios of 0, 0.05, 0.10, 0.15, and 0.20, respectively.
1. The compressive strengths ranged from 50.9 MPa to 63.5 MPa, and the elastic modulus ranged from 21.6 GPa to 25.3 GPa, which tended to increase as the SBR/cement ratio increased. The elastic modulus increased as the compressive strength increased; the correlation between the elastic modulus and compressive strength was found to be significant. The maximum compressive strain ranged from 2800 × 10⁻⁶ to 3800 × 10⁻⁶, which increased as the SBR/cement ratio increased.

2. The 28-day drying shrinkage ranged from 144 × 10⁻⁶ to 331 × 10⁻⁶, which yielded a decreasing trend as the SBR/cement ratio increased. Also, the drying shrinkage rate drastically increased between the curing ages of 5 and 10 hours.

In previous studies, Chandra et al. [10] reported the thermal expansion coefficient of polymer-modified cementitious mortar to be 9 × 10⁻⁶/°C to 10 × 10⁻⁶/°C, stating that the thermal expansion coefficient is directly influenced by that of the aggregate used, such as ordinary cement mortar. Ohama [30] showed that the linear thermal expansion coefficient of SBR-modified cementitious mortar was in the range of 7.7 × 10⁻⁶/°C to 8.6 × 10⁻⁶/°C for the polymer/cement ratio range of 0.10 to 0.20, and the linear thermal expansion coefficient of unmodified mortar was similar at 7.9 × 10⁻⁶/°C. Conversely, the linear coefficient of the thermal expansion of hydrated cement paste varied between about 11 × 10⁻⁶ and 20 × 10⁻⁶/°C [31], while those of concrete mixtures with different aggregate types were approximately 6 × 10⁻⁶/°C to 12 × 10⁻⁶/°C [19]. Compared to these thermal expansion coefficient values, the results obtained in the present work were smaller than those of paste but similar to those of concrete mixtures.

As explained above, previous studies found that the thermal expansion coefficient of SBR-modified and ordinary cementitious mixtures tends to be greatly affected by the materials used, including aggregates. However, in this study, the cement, silica sand, fly ash, and silica fume content were kept constant; only the SBR/cement ratio was used as a variable. The results of this study demonstrate that the thermal expansion coefficient increase was affected by the addition of SBR latex. This result can easily be understood by comparing the significantly greater thermal expansion coefficient of polymers such as ethylene vinyl acetate (EVA) and polyethylene (PE) to that of cementitious mortar and concrete [32]. However, the difference from ordinary cementitious mortar or concrete was not substantial, so it was determined that the SBR-modified cementitious mixtures can be used as a 3DAC material.

6. Conclusions

In this study, the dimensional stability of SBR-modified cementitious mixtures was investigated for 3DAC applications. The following conclusions were drawn:

1. The compressive strengths ranged from 50.9 MPa to 63.5 MPa, and the elastic modulus ranged from 21.6 GPa to 25.3 GPa, which tended to increase as the SBR/cement ratio increased. The elastic modulus increased as the compressive strength increased; the correlation between the elastic modulus and compressive strength was found to be significant. The maximum compressive strain ranged from 2800 × 10⁻⁶ to 3800 × 10⁻⁶, which increased as the SBR/cement ratio increased.

2. The 28-day drying shrinkage ranged from 144 × 10⁻⁶ to 331 × 10⁻⁶, which yielded a decreasing trend as the SBR/cement ratio increased. Also, the drying shrinkage rate drastically increased between the curing ages of 5 and 10 hours.
3. The coefficient of thermal expansion was found to range from $5.8 \times 10^{-6}/^\circ C$ to $12.2 \times 10^{-6}/^\circ C$. The coefficient increased as the SBR/cement ratio increased. The thermal expansion coefficient of SBR-modified cementitious mixtures was not clearly different as compared to that of ordinary cementitious mixtures.

As detailed above, the elastic modulus, drying shrinkage rate, and thermal expansion coefficient of SBR-modified cementitious mixtures were experimentally determined. The results obtained will be useful in considerations of dimensional stability when engaging in 3DAC construction.

**Author Contributions:** Conceptualization, J.Y. and J.H.Y.; Funding acquisition, J.H.Y.; Designed the experiments, J.Y. and J.H.Y.; Performed the experiments and analyzed the data, K.K.K. and H.J.L.; Writing—original draft, J.Y. and K.K.K.; Writing—review & editing, J.Y. and J.H.Y.

**Funding:** This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (No. NRF–2018R1D1A1B07048681) and the Ministry of Science & ICT (No. NRF-2015R1C1A1A01052102).

**Conflicts of Interest:** The authors declare no conflicts of interest.

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