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# Effect of By-Pass Filter Dust on Durability of Self-Compacting Concrete †

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**Abstract:** By-pass filter dust (BPD) is one of the main by-products produced and collected during the cement production process, being a potential atmospheric and subsoil pollutant. In this paper, the utilization of BPD by partially replacing a conventional filler such as marble powder with regard to the durability and transport properties of Self-Compacting Concrete (SCC) is thoroughly investigated. More specifically, BPD's incorporation effect was evaluated after conducting a series of tests related to SCCs' water absorption, sorptivity, water permeability, chloride diffusion coefficient, carbonation and freeze and thaw resistance. The above-mentioned test results demonstrated that BPD, thanks to its high pozzolanic reactivity in conjunction with its filler effect, contributed to the production of SCC of a denser cementitious matrix, which, in turn, lead to improved durability.

**Keywords:** Self-Compacting Concrete; by-pass filter dust; sustainability; durability; carbonation; freeze and thaw

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## 1. Introduction

The clear need to ensure durable high-performance concrete, regardless of the quality of casting and compaction, led to the conception and creation of Self-Compacting Concrete (SCC) in Japan in the 1980s [1]. SCC, thanks to its excellent rheological properties and segregation resistance, ensures high filling and passing ability under its own weight, without any vibration or compaction. Moreover, when it comes to hardened concrete properties, the higher level of homogeneity and the denser matrix microstructure contribute to the improved mechanical properties and durability in comparison to conventional vibrated concrete [2,3]. Both advanced rheological properties and denser microstructures presuppose certain modifications in the ingredients and proportions during mix designing [4,5].

Traditionally, and in order to achieve the above-mentioned desired properties, SCC contains higher amount of cement, chemical admixtures and fine aggregates compared to vibrated concrete mixtures, leading to a higher carbon footprint and lower sustainability. On the other hand, appropriate modifications to SCCs' mix designs by adding industrial waste materials, reducing cement content and minimizing the chemical admixture consumption, could greatly improve the eco-efficiency of the concrete [6]. Nevertheless, incorporating raw industrial by-products without subjected them to additional processing, as they may contain dangerous impurities in conjunction with low cement content, could lead to the creation of SCC of dubious quality and performance. Thus, a comprehensive series of tests should be conducted not only regarding the rheology or the mechanical properties but also mainly on the subject of long-term concrete durability.

Among the traditional fine filler materials that are found in the literature and have been extensively examined in light of their effects on the rheology, mechanical properties and durability of SCC, the most commonly referenced are fly ash, silica fume, rice husk ash and ground blast furnace slag or limestone powder, categorized as pozzolanic or latent hydraulic additions (Type II) and nearly inert additions (Type I) in accordance with EFNARC guidelines [2,7,8]. Moreover, apart from the above, more and more industrial by-products or recycled materials are being used as cement or fine aggregate substitutes [9,10]. A special category of industrial by-products that, in recent years, has attracted increasing interest is the industrial wastes of the cement industry. One of the main by-products that is produced and investigated is by-pass dust (BPD) [11–13]. Nevertheless, due to its relatively high content of alkalis, sulfates and free lime, the concentration of it has a direct dependence on the particle size distributions of raw materials that compose the clinker, as well as the chloride content, and they require a thorough investigation in terms of mechanical and physical properties and long-term durability properties of SCC [14].

In the experimental program of the present paper, the durability of SCC containing BPD, replacing conventional marble powder at different ratios, was evaluated by conducting a series of tests, such as open porosity, capillary absorption, air permeability, chloride penetration, carbonation and freeze and thaw resistance tests.

## 2. Materials and Methods

### 2.1. Materials

Aggregates including crushed limestone (LS) in three nominal grades (0/4, 4/8 and 8/16 mm) and Portland Cement CEM I 42.5R were used in accordance with EN12620:2013 and EN 197-1:2011, respectively. Marble powder (MP), which constitutes a conventional fine filler material containing approximately 55% CaO (Loss of Ignition: 43.4%), was used, as was by-pass dust (BPD), which mainly consists of lime and a mineral phase that encompasses $SO_4^{2-}$, alkalis and $Cl^-$, while traces of $C_2S$ are also often found. Lastly, tap water and a modified polymer-based superplasticizer (SP), conforming to EN 934-2, were used. The main physical properties of the LS used, as well as the corresponding physical properties of cement powder, MP and BPD, are shown in Table 1 [15].

**Table 1.** Physical properties and characteristics of raw materials used [15].

| Property or Characteristic | Cement | MP | BPD | LS (0/4) | LS (4/8) | LS (8/16) |
|---|---|---|---|---|---|---|
| Specific Gravity | 3.15 | 2.70 | 2.80 | 2.69 | 2.71 | 2.71 |
| Specific Surface Area ($cm^2/g$) | 3470 | 12,700 | 5000 | - | - | - |
| d10 (μm) | 4.74 | 1.44 | 12.95 | <63 | 1900 | 5790 |
| d50 (μm) | 19.82 | 4.88 | 50.72 | 890 | 4310 | 7940 |
| d90 (μm) | 57.41 | 12.27 | 115.63 | 3150 | 6400 | 10,800 |

### 2.2. Mix Design

REF1 and REF2 represent the two reference compositions with MP contents of 200 kg/m$^3$ and 250 kg/m$^3$, respectively. They were produced with water-to-cement (w/c) ratios 0.60 and 0.66, respectively, by maintaining a constant water-to-powder (w/p) ratio and a cement content of 0.36 and 300 kg/m$^3$, respectively. The above mixtures were altered by replacing 100 kg and 150 kg of MP with BPD, for BPD1 and BPD2, respectively. The detailed mix design of the above-mentioned compositions is shown in Table 2, where the SP dose required to obtain the desired slump flow range (690–710 mm) is also given.

**Table 2.** Mix proportions and ratios of the SCC mixtures produced.

| | Water (kg/m$^3$) | Cement (kg/m$^3$) | MP (kg/m$^3$) | BPD (kg/m$^3$) | LS (0/4) (kg/m$^3$) | LS (4/8) (kg/m$^3$) | LS (8/16) (kg/m$^3$) | SP/cement (%) | w/c | w/p |
|---|---|---|---|---|---|---|---|---|---|---|
| REF1 | 180 | 300 | 200 | 0 | 900 | 560 | 240 | 1.7 | 0.60 | 0.36 |
| BPD1 | 180 | 300 | 100 | 100 | 900 | 560 | 240 | 3.1 | 0.60 | 0.36 |
| REF2 | 198 | 300 | 250 | 0 | 900 | 525 | 225 | 1.5 | 0.66 | 0.36 |
| BPD2 | 198 | 300 | 100 | 150 | 900 | 525 | 225 | 2.7 | 0.66 | 0.36 |

### 2.3. Testing

All durability tests were conducted at the age of 90 days. Capillary absorption and open porosity were measured by conforming with ASTM C 1585 and ASTM C 642, respectively, while the water penetration depth and chloride permeability coefficient were determined in accordance with EN 12390-8 and EN 12390-18, respectively. Furthermore, the carbonation depth was measured in consonance with EN 12390-10 for cubic specimens (70 × 70 × 70 mm$^3$) after being exposed to the $CO_2$ environment for 28, 70, 130 and 180 days, while freeze and thaw resistance was evaluated in accordance with EN12390-9.

## 3. Results and Discussion

In Figure 1, the capillary absorption (bars) and the open porosity (marks) are illustrated for all four SCC mixtures. After comparing the reference mixtures of the two series, we detected that capillary absorption of REF1 was almost 30% less compared to the corresponding absorption of REF2. The above finding is elucidated based on the higher water-to-cement ratio of the REF2 composition (0.66 instead of 0.60), as lower w/c generates a decrease in concrete capillary voids of lower size, as Uysal also claimed [16]. BPD incorporation decreased the capillary absorption to a greater extent, namely by approximately 38% for both series, which can be related to the pozzolanic reactivity of BPD that contributes to the production of cement paste of a denser structure. Additionally, replacing a part of MP with BPD, which constitutes a fine filler material with various particle size distributions, leads to a higher packing density and even denser matrix microstructure (filler effect). As was expected, the open porosity of REF2 is approximately 31% greater than that of REF1, as the higher water-to-cement ratio results in the formation of additional permissible voids. On the other hand, BPD incorporation, in spite of its pozzolanicity and the filler effect, managed to positively impact the results, as the values measured remained almost constant. It seems that mechanism of open porosity formation is mainly governed by the w/c ratio.

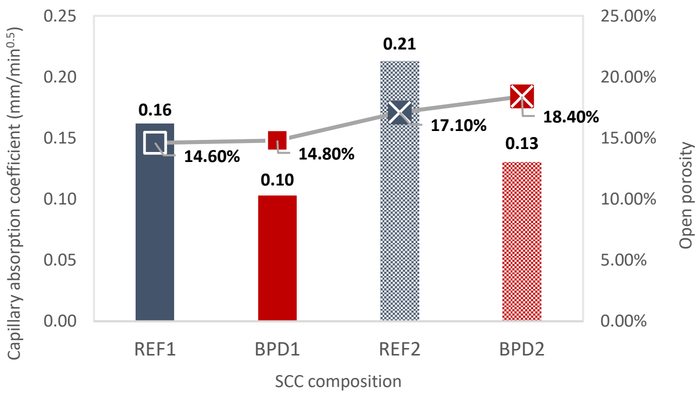


**Figure 1.** Capillary absorption (bars) and open porosity (marks) for SCC compositions.

Figure 2 illustrates the water penetration depth (primary axis bars) and chloride migration coefficient (secondary axis bars). As REF2 had a greater w/c ratio, the penetration depth measured accounts for 28 mm, which is approximately 65% higher than the corresponding penetration depth for REF1 (17 mm). Based on the above results, the effect of the w/c ratio on the structural density of concrete and, consequently, on the water permeability is confirmed. The aforementioned percentage could be greater; however, the lower coarse aggregate content in series 2 specimens leads to the partial elimination of the phenomenon of increasing permeability as the total interfacial transition zone between cement paste and aggregates is reduced, leading to minimized microcracks, which constitute a key factor for the high permeability of concrete. Prominent improvement was measured in terms of water permeability for BPD1 and BPD2, as they had their water penetration depths decreased by 24% and 25%, respectively, in comparison to the corresponding reference specimens. The above-mentioned results can be comprehended by taking into account the pozzolanicity of

BPD that increases the denseness of the concrete and, principally, the microstructure of the interfacial transition zone between cement paste and limestone aggregates. Additionally, creating a ternary powder mixture by adding a third type of powder, apart from cement and MP, leads to a denser cementitious matrix structure due to the higher presence of the filler effect [17,18]. When it comes to the chloride permeability coefficient, a higher water content and higher w/c of REF2 led to a 60% higher chloride permeability index compared to REF1. The chloride permeability coefficient was also negatively affected by BPD incorporation, as significant increases of 56% and 33% were noticed for series 1 and series 2, respectively. The above results could be primarily attributed to the $Cl^-$ content of BPD, which accounts for 2.16%.

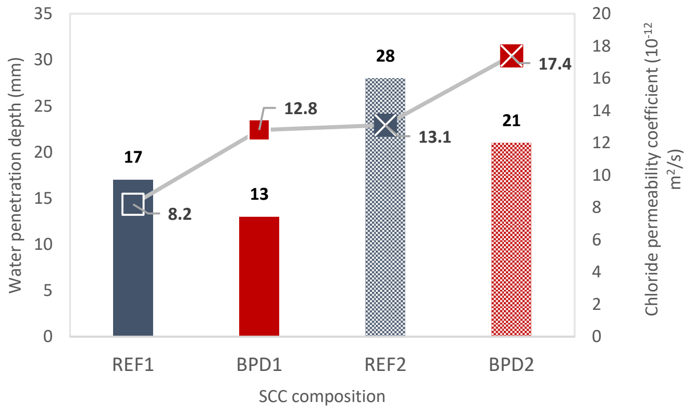


**Figure 2.** Water penetration depths (bars) and chloride coefficients (marks) for SCC compositions.

In Figure 3, the carbonation depth progress at the ages of 28, 70, 130 and 180 days, as is illustrated. Increasing w/c leads to increased gas permeability, which, in turn, leads to the reduced carbonation resistance of REF2 in comparison to the corresponding resistance of REF1. Hence, after 180 days of exposure to a high-$CO_2$ environment, the carbonation depth measured for REF2 was 24% higher than that of REF1. BPD incorporation highly contributes to the reduction in the carbonation depth. BPD1 and BPD2 carbonation depths after 180 days were lower by approximately 66% and 50% than the corresponding depths of REF1 and REF2, respectively.

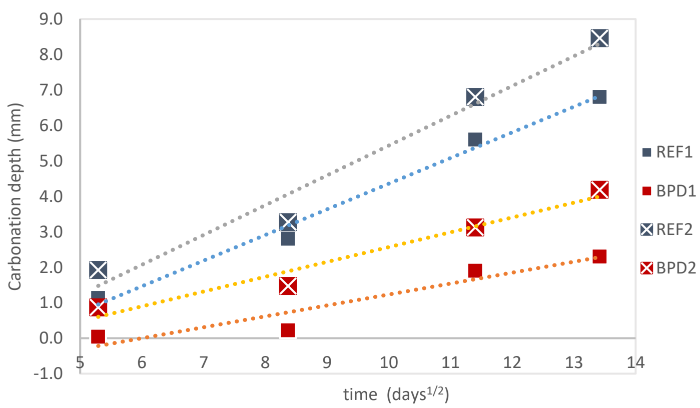


**Figure 3.** Carbonation depth progress with respects to time for SCC compositions.

In Figure 4, the spalling content for each SCC composition produced after several freeze and thaw cycles is illustrated. Despite the higher water permeability, the spalling content for REF2 is lower than the corresponding content for REF1. This can be explained by the fact the higher w/c leads to a less dense cement paste structure and a greater void content, which contributes to the relieving of the stresses developed via ice crystal growth in cementitious matrix pores. Furthermore, up to the 28th cycle, compositions of lower w/c exhibit better frost resistance than the corresponding compositions of higher w/c. This is attributed to the fact that for the first cycles, the dense concrete structure obstructs water from penetrating; however, once it penetrates, the damage due to water expansion stresses is more significant. Moreover, BPD incorporation led to SCC mixtures with reduced freeze and thaw resistance, as for BPD1 and BPD2, a significantly higher spalling content was collected and weighed. What is worth noting is that the difficulty of water penetration for BPD1 counteracts the less dense microstructure of BPD2, which allows the expanding stresses to be relieved, ultimately leading to similar results.

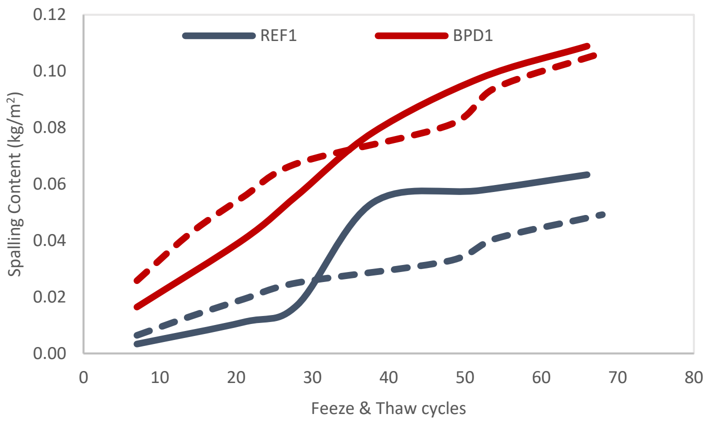


**Figure 4.** Spalling contents of SCC compositions after freeze and thaw cycles.

## 4. Conclusions

After producing SCC by partially replacing conventional MP with BPD, the below conclusions were drawn:

- ✓ BPD incorporation led to SCC with toned down water penetration depth as a consequence of the denser microstructure provided by the pozzolanic reaction of BPD.
- ✓ The pozzolanic reactivity of BPD also led to SCC compositions with an enhanced capillary absorption coefficient. Concurrently, the open porosity was not notably affected by BPD's existence.
- ✓ The chloride diffusion coefficient was adversely affected by BPD incorporation, which could be partly attributed to its higher $Cl^-$ content compared to MP.
- ✓ The carbonation resistance values of compositions with BPD were significantly upgraded on account of the decreased gas permeability due to high pozzolanicity of BPD.
- ✓ The denser microstructure of the cement paste of SCC containing BPD leads to decreased freeze and thaw resistance.

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