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Mixture Optimization of Concrete Paving Blocks Containing Waste Silt

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Abstract: Most of the waste materials recycled for the production of new construction materials are by-products of various manufacturing processes, such as the aggregate washing process. Recycling such materials is of paramount importance since it could reduce the adverse environmental impacts resulting from landfilling. Various studies have attempted to recycle different types of waste materials and by-products into concrete paving blocks. However, the availability of literature on concrete paving blocks containing waste silt is quite scarce. Thus, the current paper focuses on mix design optimization and production of concrete paving blocks containing high amounts of waste silt resulting from the aggregate production process. Using the mixture Design of Experiments (DOE), 12 sets of concrete paving blocks with different aggregate blends were produced to optimize the mix design. Once the final mix design was achieved, the physical and mechanical properties of the concrete paving blocks were investigated following the EN 1338 standard. Shape and dimension measurements and various tests, including water absorption, tensile splitting strength, abrasion resistance, and slip/skid resistance were conducted on the experimental concrete paving samples. Overall, the produced concrete paving blocks showed promising properties for future applications in pedestrian walking paths.

Keywords: Design of Experiments; waste silt; paving blocks; recycled concrete; pedestrian footpaths

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1. Introduction

As time has passed, sustainability has gained more and more interest amongst researchers, authorities, and politicians and has shifted far away from just being a concept. Nowadays, millions of contexts are available that discuss sustainability from different viewpoints. The construction sector, for instance, has been focusing on various aspects of sustainability and many efforts have been put into producing eco-friendly and sustainable infrastructure. Out of the several examples and approaches, one could point out the recycling of waste or by-products into construction materials.

Most of the waste materials are secondary products of various manufacturing processes, such as the aggregate washing process, stone quarries, etc. Recycling such material is of paramount importance since it could reduce the adverse environmental impacts due to landfills. These kinds of materials have been used in the production of several products, such as geopolymers, cement mortars, artificial aggregates, and pavements [1–7].

Concrete paving blocks are building elements being used in roads, pedestrian walks, driveways, and parking lots. Various studies have attempted to build paving blocks containing waste products [8,9]. This would decrease the use of natural aggregates, where approximately up to 3 billion tons of non-renewable natural aggregates are demanded by the construction sector [10].

For instance, both conventional construction and demolition (C&D) and waste material from concrete and ceramic precast production was reused as a source of aggregates to produce new concrete floor blocks. It was claimed that the latter waste material outperformed C&D waste adopted for the same application [11]. The specification of the produced floor blocks was in line with the European standards even at 100% replacement. Similar results were obtained when 100% recycled concrete aggregates (RCA) were used for the manufacturing of new paving blocks [12]. The authors indicated a slight decrease in the strength of the produced samples. However, the experimental paving blocks fulfilled the accepted limits. A different approach was adopted by Penteado et al. (2016), who used ceramic polishing waste and ceramic tile waste as a partial replacement for cement and sand, respectively, for the production of paving blocks [13]. The findings suggested that the replacement of 30% fine aggregate or 20% cement with ceramic tile wastes to produce paving blocks is suitable for heavy vehicle traffic. Similar methods of replacing waste material with cement to produce concrete paving blocks have been investigated by various researchers [14–16].

Natural aggregate production includes a washing process that cleans the aggregates from dirt and mud. During limestone aggregate production, the water used could be contaminated with silt particles. By nature, silt particles are bigger than clay and are formed from two main crystal layers of silica (tetrahedral) and alumina (octahedral). Similar to clay materials, silt is not a favorable material, and its application in infrastructure requires special attention [17]. Several studies have investigated the feasibility of using clay materials in various applications [18]. For instance, a study aimed to investigate the inclusion of RCA and crushed clay bricks (CCB) on the mechanical properties of recycled concrete [19]. The results indicated that 50% of CCB decreased the workability of the concrete samples, making them hard to compact and mix. CCB influenced the compressive and splitting tensile strength the most.

Partition and paving blocks were produced from recycled marine sediments consisting of gravel, sand, silt, and clay [20]. The paving blocks produced with raw sediment had the highest profit based on the cost–benefit assessment. As a similar concept, the sedimentation of a mud dam was extracted and efforts were made to produce bricks and building materials [21]. The extracted sediments were composed of 74% of silt. To ensure better performance, lime, cement, and glass powder and fiber were also included in the brick mixtures and the compressive strength and flexural strength of the samples were studied. Overall, it was concluded that some of the mixtures had the potential to be used as building materials.

Soil containing gravel, sand, silt, and clay was stabilized with cement to produce mud-based paving blocks [22]. The splitting tensile strength of the mud blocks was suitable for pedestrian footpaths. The final composition of the mud paving blocks suggested that soil containing 5% fine particles could be used.

In a different approach, waste brick powder (WBP) was added to stabilize silt with high plasticity properties [23]. The WBP ranged between 6 and 30% of the dry soil weight. The authors concluded that the addition of WBP increased the compressive strength, California Bearing Ratio, and density of the silt, whereas various parameters such as Atterberg limits, linear shrinkage, and free swelling decreased.

The feasibility of using limestone dust and cement to produce masonry blocks was investigated by Galetakis et al. (2004) [24]. The cylindrical samples presented compressive strengths above 7 MPa, indicating the suitability of using quarry waste and cement mixtures to produce bricks.

To control and manage stormwater, efforts were made to produce porous clay paving blocks containing rice bran [25]. The clay soil constituted about 14% silt and clay particles. Interestingly, the porous bricks were able to meet the requirements of the WHO standard in terms of wastewater reuse application. It was further indicated that the application of rice bran below 10% could provide sufficient strength and drainage, allowing the bricks to be used in lightweight pedestrian areas.

The available data on concrete paving blocks containing waste silt are quite scarce. Thus, the present study aimed to investigate the feasibility of including high amounts of silt in concrete paving blocks. For this purpose, two objectives were set: the optimization of paving-block mix design through the Design of Experiments (DOE) approach and the physical and mechanical characterization of the obtained paving blocks based on the EN 1338 standard.

2. Materials and Methods

The production of paving blocks was divided into two different sections. In the first section (Phase I), a total of 12 different aggregate combinations were defined by the Design of Experiments model. Consequently, a total of 12 mixtures with different aggregate blends were produced and the tensile splitting strength of each sample was applied to the DOE model. JMP software was used to optimize the mathematical model and an optimized model was proposed to identify the best aggregate blend. In Phase II, a total of 9 samples were produced using the proposed aggregate blend, which were characterized based on the EN 1338 standard.

2.1. Materials

The aggregates including gravel (4–8 mm), sand (0–4 mm), and silt were provided by Società Azionaria Prodotti Asfaltico Bituminosi Affini (S.A.P.A.B.A. s.r.l.). The recorded values for bulk density (EN 1097-6), sand equivalent (EN 933-8), and harmful fines (EN 933-9) of the sand and gravel are presented in Table 1. A 42.5 R cement was used for the paving blocks (Buzzi Unicem, Casale Monferrato, Italy). In addition, a specific additive that allows the use of swelling clays or aggregates with very high fines was used.

Table 1. Sand and gravel physical properties.

Material	Bulk Density (g/cm^3) EN 1097-6	Sand Equivalent (%) EN 933-8	Harmful Fines (gMB/Kg) EN 933-9
Sand (0–4 mm)	2.616	92	0.5
Gravel (4–8 mm)	2.667	-	-

The silt is a by-product of the limestone aggregate washing process and is stored in special sedimentation lakes of S.A.P.A.B.A. The silt is taken from the lakes, oven-dried, and crushed using a Los Angeles machine. The pulverized silt was then used in the production of concrete paving blocks. Figure 1 shows the overall process of the silt preparation. The elemental and compound analysis of the waste silt was examined using X-ray fluorescence (XRF) (Shimadzu, Kyoto, Japan) and X-ray powder diffraction (XRD) (Rigaku, Tokyo, Japan), respectively. The raw silt, with a pH of 7.0, met all the requirements of the Italian legal limits regarding the amount of hazardous material (Table 2). The mineralogical evaluation revealed the presence of quartz (32%), calcite (28%), illite/micas (21%), and chlorite (5%), with traces of dolomite and feldspars (Figure 2).

Figure 1. Obtained silt from sedimentation lakes. During aggregate production (**A**) the produced silt is pumped to the sedimentation lakes (**B**). The material is oven dried and finely crushed prior to final use (**C**).

Table 2. Chemical oxides present in waste silt.

Parameter	Value (%)
SiO_2	43.5
TiO_2	0.6
Al_2O_3	12.5
Fe_2O_3	6.1
MnO	0.2
CaO	15.8
Na_2O	1.0
K_2O	1.9
P_2O_5	0.1
MgO	3.0

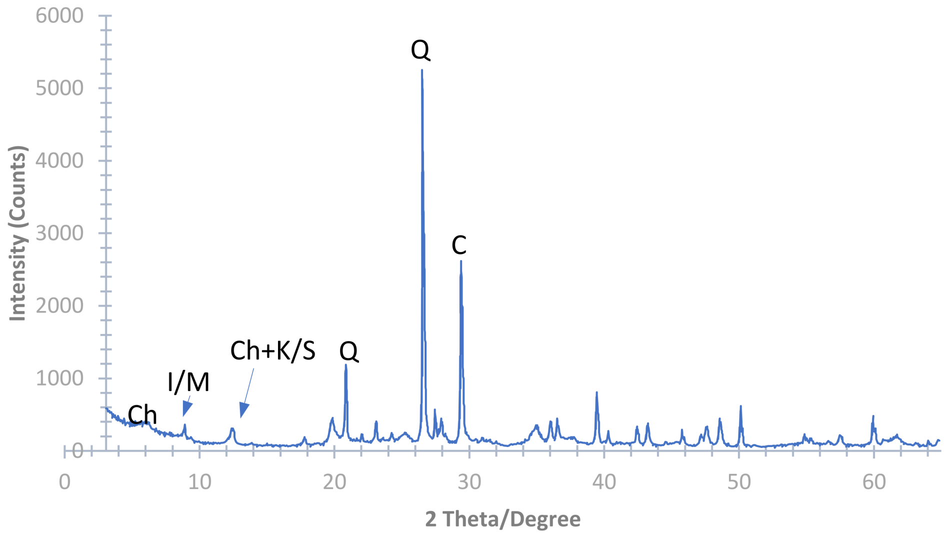

Figure 2. Waste silt XRD analysis reveals a crystalline structure observed as sharp peaks in the diagram. Q = quartz, I/M = illite–mica, Ch = chlorite, K/S = kaolinite/serpentine.

2.2. Design of Experiments and Mixture Optimization

Design of Experiments (DOE), or statistical experimental design, is a profound approach and methodology for model building and optimizing multivariable systems [1,2]. For instance, tackling and optimizing problems related to the effect of process factors on production properties could be managed through fractional factorial or central composite design methods. However, when it comes to mixture preparation and optimization applications, the DOE will include a mixture design to analyze and evaluate the effect of different components on the final properties of the blend. In other words, the mixture designs aim to optimize blends, where the proportion of the components or ingredients affect the final properties of the mixture. Several available products such as plastics, paints, food, and pharmaceuticals are examples of mixtures and blends that are sold commercially worldwide. In such cases, researchers can benefit from the mixture-design technique to optimize such mixtures based on desired criteria. In a mixture design experiment, the dependent factors are proportions of different components of a blend and the total sum of all factors for each run are equal to 1 or 100%. Thus, the mixture components cannot be altered independently of one another. In such cases, the mixture experimental data cannot be shown in cubes but rather in the form of triangular geometries, more specifically ternary plots. A full description of mixture design and its application is summarized by Eriksson et al. (1998) [26]. An n-component mixture is presented in Equation (1).

$$0 \le x_i \le 1 \; i = 1,\, 2,\, 3,\, \ldots,\, n \; \sum_{i=1}^{n} x_i = 1 \tag{1}$$

where the proportion of the *i*th ingredient/factor is represented by x_i.

Various studies have benefitted from the mixture design method for optimizing their mixtures and blends. For instance, the DOE method was used to predict the compressive strength of concrete samples from early-aged mixtures. A total of 114 samples were tested and the ACI stepwise method was applied. The authors indicated that the suggested models were capable of predicting the 28th day compressive strength of the concrete samples [27]. A mixture design was applied by [28], where different combinations of polymer concretes including resin, aggregates and microfiller were studied. The mentioned components were also limited through upper and lower values. Various mechanical properties such as compressive, flexural, tensile, and splitting tensile strength were tested and included in the model as the responses. The authors suggested an overall mixture being optimized based on the maximized desirability of all responses [28]. Defining upper and lower limits for variable components and limiting the sum of two or three variables to a certain value is common and results in producing an irregular experimental region [26]. In some cases, researchers benefit from multiple optimization methods and combine various numerical methods with DOE. For instance, both a numerical method and a DOE were used to optimize the thermal performance of lightweight concrete building blocks [29]. The authors optimized the blocks for the best thermal insulation, keeping the manufacturing cost at a minimum.

For the current study, JMP® software (Version 14.0. SAS Institute Inc., Cary, NC, USA, 1989–2019) was used to produce the mixture designs. The three main components (input variables) were selected as gravel, sand, and silt, and the response output was selected as the tensile splitting strength (T). Producing pure mixtures only containing one component was not in favor of the research. Thus, the components were limited to lower (0) and upper boundaries (1) corresponding to 0 and 100%, respectively (Table 3).

Table 3. Mix design components: upper and lower boundaries.

Indicator	Upper	Lower
Gravel	0.00	0.65
Sand	0.00	0.65
Silt	0.00	0.40

The DOE produced a total of 12 randomized runs. More specifically, the second-degree model was produced by selecting the forward stepwise approach. Furthermore, minimum BIC (Sawa Bayesian information criterion) was selected over AICc (corrected Akaike information criterion) due to having a lower value. The BIC and AICc are information criteria methods used to assess model fit while penalizing the number of estimated parameters. The mixture suggested for each run was used to produce the concrete paving block tested in terms of tensile splitting strength. The model was further analyzed using JMP software and the profiler tool was benefitted to optimize the final aggregate gradation. Further details are discussed in Section 3.1.

2.3. Concrete Paving-Block Preparation

A total of 12 concrete mixtures each with three replicas were created based on the DOE model design. To produce each set, cement and proportioned aggregates were mixed. Water and the special additive were added to the mixture. For each mixture, the aggregate-to-cement ratio (A/C) was fixed at 4.62 and enough water was added to reach a slump value of 0. The A/C ratio was recommended by a local paving-block producer. The material was then transferred to special plastic molds. The samples were demolded after 24 h and were cured for 28 days before testing. Figure 3 illustrates the mixing process and the final demolded samples.

Figure 3. Concrete paving block specimen. Each set of blocks contains 3 repeats and are numbered from right to left. The mixture design of each block is presented in Table 4.

2.4. Concrete Paving-Block Characterization

Once the optimized mix design from the DOE analysis was achieved, the suggested blend was adopted to produce paving blocks for the following characterization based on the EN 1338 standard:

- Shape and dimensions;
- Weathering resistance in terms of water absorption;
- Tensile splitting strength (T);
- Abrasion resistance;
- Slip/skid resistance.

This European standard is specific to concrete paving blocks and classifies concrete bricks into various categories based on their performance.

3. Results

3.1. Phase I: Mix Design Optimization through the Design of Experiments Approach

Cement concrete mixtures are composed of various ingredients, such as cement, aggregates, additives, and water, where all components add up to 100%. The composition of aggregates including coarse, fine, and fillers of concrete mixtures also follows the same principle, i.e., the sum of the components equals 1 (100%). An effective method of studying such blends, where changes in the mixture composition could affect various outcomes (responses), is by applying the mixture design method. Consequently, the effect of various aggregate compositions (gravel, sand, and silt) on the splitting tensile strength (T) of cement concrete paving blocks was studied using the DOE method.

In this study, the input variables were gravel, sand, and silt (%), and the T of the resulting mixtures was selected as the response. To provide a model, the Design of Experiments indicated 12 randomized runs each with a different aggregate gradation. T was obtained based on the EN 1338 standard for each mixture and the average values were included in the DOE (Table 4).

The highest value for T was obtained for the ninth sample with 0% silt (2.8 MPa), whereas the lowest value (0.4 MPa) was related to the first mixture with 40% silt. Furthermore, the usage of a higher amount of silt increased the water-to-cement ratio of the mixture, limiting the compaction rate. Low T values were also observed for samples lacking coarse aggregates (gravel), such as samples 2, 6, and 12. A good gradation curve is vital to having desirable strength. A very dense or gapped gradation could tamper with the final compaction, resulting in lower mechanical values.

Table 4. Design of experimental data.

Run		Gravel (%)	Sand (%)	Silt (%)	T (MPa)
A	1	0.3	0.3	0.4	0.4
F	2	0	0.6	0.4	0.91
I	3	0.5	0.5	0	1.87
D	4	0.625	0	0.375	0.67
G	5	0.65	0.175	0.175	1.24
E	6	0	0.65	0.35	0.83
B	7	0.65	0	0.35	0.47
J	8	0.65	0.35	0	1.91
K	9	0.35	0.65	0	2.8
C	10	0.6	0	0.4	0.52
H	11	0.175	0.65	0.175	1.26
B	12	0	0.625	0.375	0.47

The summary of fit for the produced model is presented in Table 5, indicating an R^2 value of 90.55. The produced model was then used to predict the corresponding T value for each of the 12 mixtures. The actual versus the predicted T values are depicted in Figure 4, where the blue line indicates an average T of approximately 1.1 MPa. Table 6 shows the significance of adding a term to a model given that the other terms are already entered. For instance, sand added the highest significance to the model, followed by gravel. On the other hand, the silt parameter did not have a significant effect on the model ($p < 0.05$). In such cases, one could eliminate the insignificant parameter from the model, improving the overall accuracy. However, the elimination of insignificant parameters is not possible for the mixture design approach. A concrete mixture is composed of different ingredients, such as cement, water, and aggregates. By removing any of these components from the design, the produced outcome will no longer be a concrete mixture. Thus, the silt parameter was kept in the model. Moreover, the coefficient of the factors (gravel, sand, and silt) is indicated in the T ratio column of Table 6. It is observable that silt had a negative value of −0.61, indicating that an increase in the silt content decreased the overall strength of the concrete bricks. This occurred because a high amount of silt increases the need for water in the mixture, which results in lower strength values. Overall, the produced model showed a very high significance value ($p < 0.0002$), as indicated by the analysis of variance (Table 7).

Table 5. Summary of fit.

Indicator	Value
RSquare	0.91
RSquare Adj	0.87
Root mean square error	0.27
Mean of response	1.11
Observations (or sum wgts)	12

Table 6. Parameter estimates.

Term	Estimate	Std Error	T Ratio	Prob > |t|
Gravel (%) (Mixture)	1.2302425	0.475316	2.59	0.0322
Sand (%) (Mixture)	3.068301	0.502842	6.10	0.0003
Silt (%) (Mixture)	−0.570944	0.916089	−0.62	0.5505
Sand (%) * Silt (%)	−4.43013	2.750201	−1.61	0.1459

The main components of the DOE include the term "(Mixture)". These components cannot be deleted during model optimization even if they show insignificant differences.

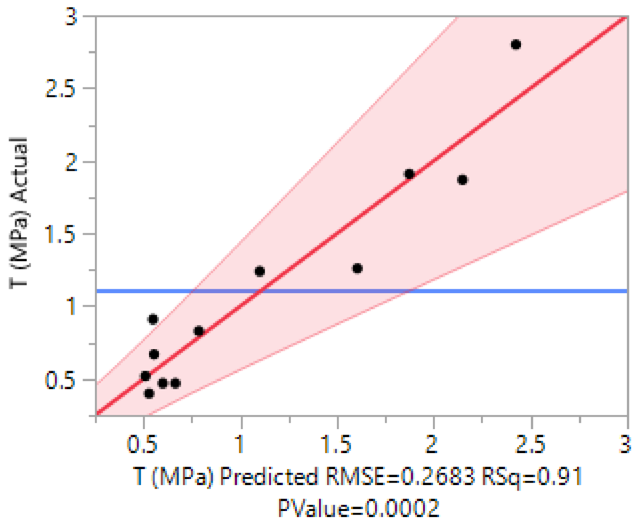

Figure 4. Actual vs. predicted T values.

Table 7. Analysis of variance for the produced model.

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	5.5204633	1.84015	25.5594
Error	8	0.5759617	0.07200	Prob > F
U. total	11	6.0964250		0.0002

The relationship between aggregate composition and T was studied by producing contour plots (Figure 5). The final percentages of silt, sand, and gravel directly affected the final strength of the brick samples. In both cases (Figure 5a, b), the highest value for T was obtained when the percentage of silt was below 5% (total aggregate weight). Moreover, to reach the maximum strength (T > 2.5 MPa), the amount of sand and gravel need to be approximately between 60 and 65% and 33 and 38%, respectively. The silt had a negative interaction with both sand and gravel, i.e., an increase in silt content resulted in lower T results. This is also observable in the contour plots, where the application of more than 30% of silt dramatically decreased the strength.

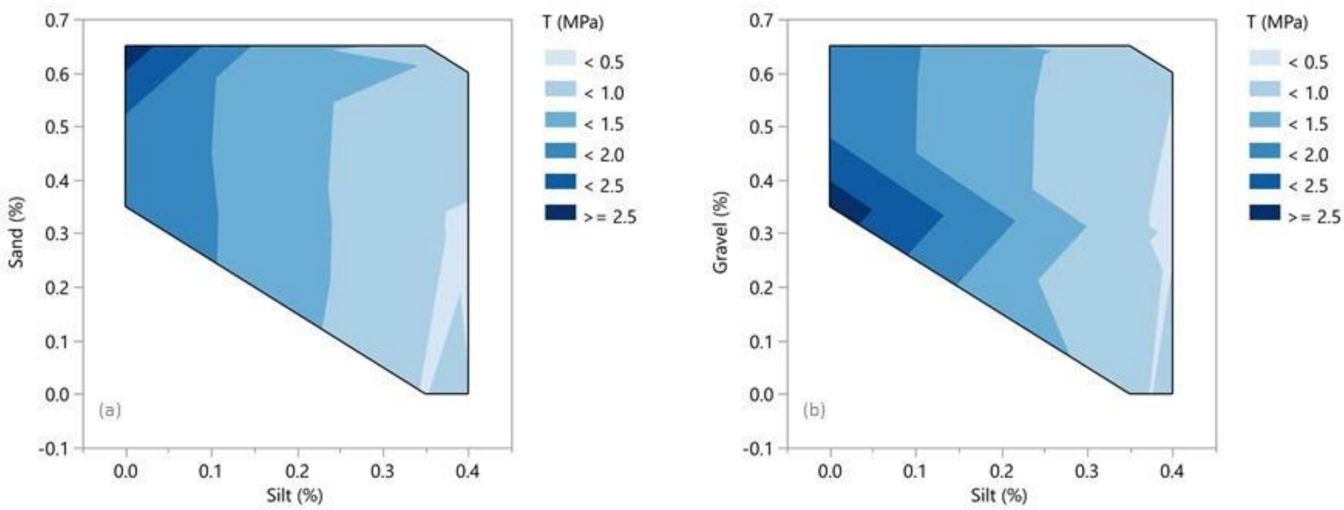

Figure 5. Contour plots for splitting tensile strength: (**a**) silt-sand and (**b**) silt-gravel.

One of the most important goals when conducting a Design of Experiments through JMP software is to benefit from its powerful optimization tools. The profiler option provides a cross-section of the model, where the curve of each factor shows the relationship with the response based on the levels of other factors. In model optimization, various factors could be considered. One approach is to use the profiler to maximize or minimize the desirability, that is, by simultaneously changing each available variable factor to achieve the target value. However, some design blends may have costly ingredients, or, on the contrary, may include waste/by-products that need to be recycled into certain products. In such scenarios, the variable factor could be fixed at a desired value and the corresponding outcome or response would be optimized accordingly. The current research aimed to maximize the amount of recycled silt in the production of concrete paving blocks. Thus, the profiler tool in the JMP software was used to optimize the concrete mixture accordingly (Figure 6). The optimum blend had an approximate T of 1.49 MPa, resulting from a mixture consisting of 15, 65, and 20% gravel, sand, and silt, respectively. The amount of silt was fixed at 20% and the remaining parameters were calculated accordingly. In Figure 6, the values presented in the brackets (1.2112, 1.76643) are the 95% confidence intervals for the tensile splitting strength values. The dotted red lines indicate the selected value for each parameter and the resulting outcome (T) of the model. The slope of the factors represents the coefficient of the parameters, which is also tabulated in Table 6. Figure 6 also includes the graphs related to the desirability factor of the mathematical model. The desirability function normalizes the responses from the lowest (0) to the highest obtainable value (1). From the desirability graphs (Figure 6) it is concluded that by using the 20% silt in the mixture, only 45.5% of the possible T values were obtained.

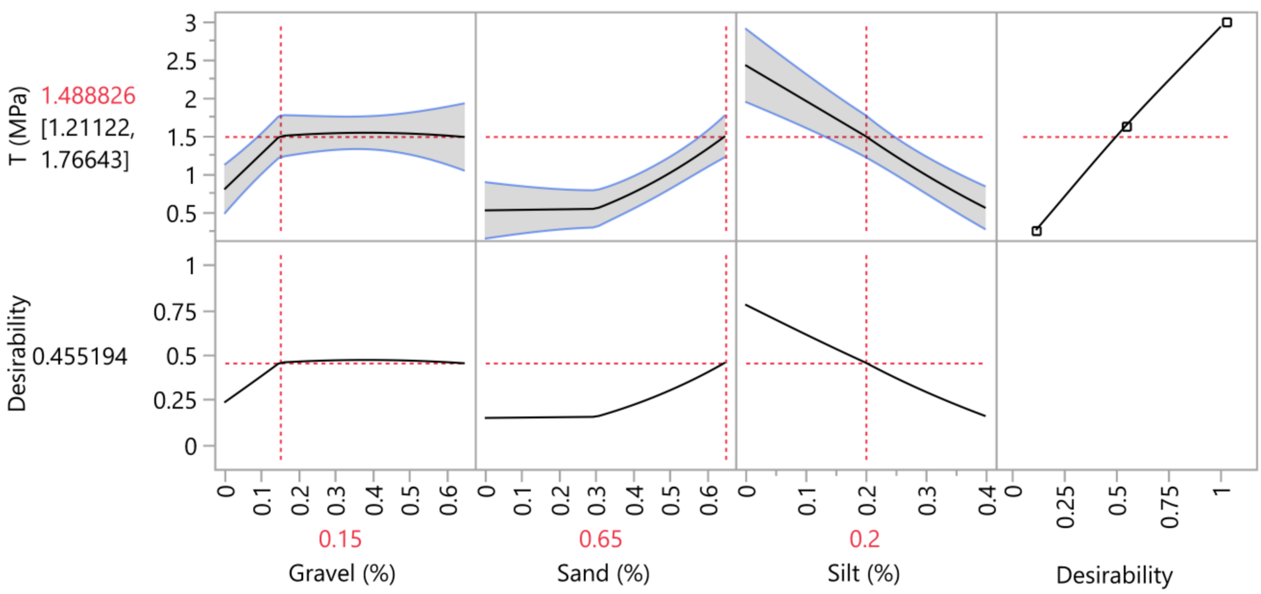

Figure 6. Model optimization using the profiler tool in the JMP software.

To further understand the model and study the relationship between different variables and their effect on the final strength, a ternary plot was produced (Figure 7).

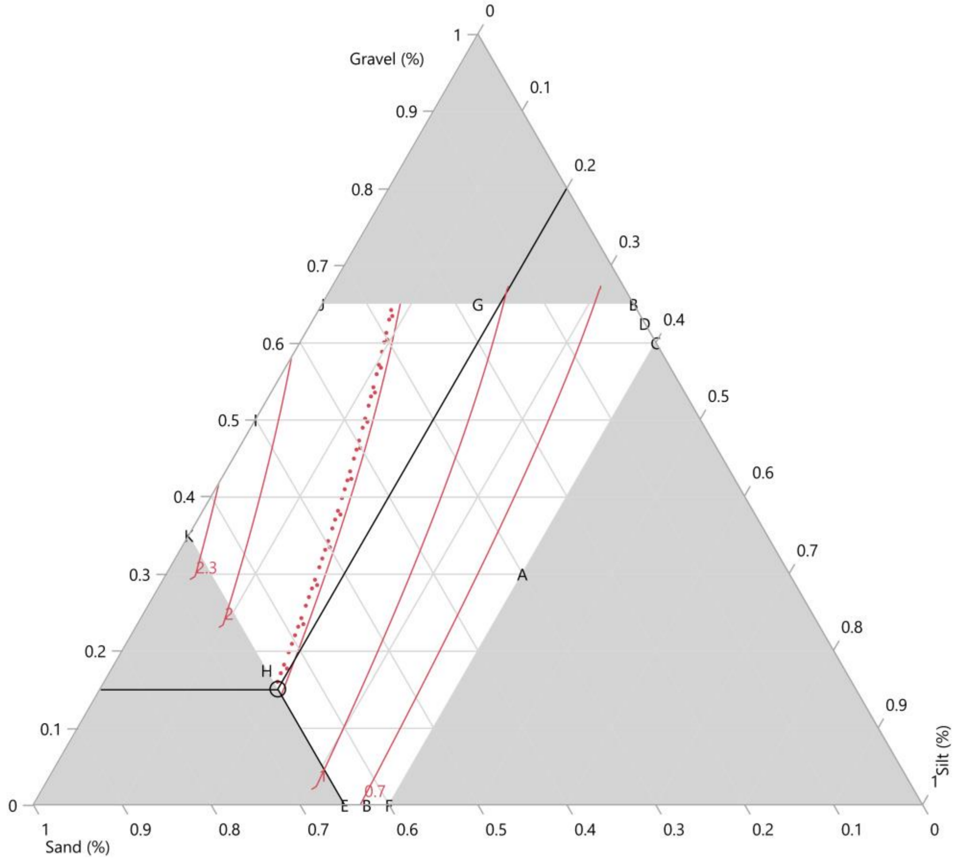

Figure 7. Ternary plot. The alphanumerical labels refer to the corresponding runs shown Table 4.

The white section represents the model area. However, the constraints applied to the variable parameters are shown in the grayed-out section of the plot. The splitting tensile strength obtained through the mechanical test for each sample (run) is designated in alphanumerical labels in the ternary plot. The labels are also included in Table 4. The marker indicates the area in the plot where the optimum mixture was achieved. In addition, the red-dotted line corresponds to a strength equal to 1.489 MPa, as obtained in Figure 6. The ternary plot also shows that a decrease in silt content and an increase in sand content increased the overall strength of the samples. The plot shows that the same value of 1.489 MPa was achievable using less silt, that is, 8.5% instead of 20%. However, this would lead to recycling less silt into concrete paving blocks.

All in all, according to the profiler optimization, the final values selected for gravel, sand, and silt were calculated as 15, 65, and 20%, respectively. The final mixture was conducted based on the optimized aggregate gradation, keeping the aggregate-to-cement ratio at 4.62. Similar to the production of the first mixtures, enough water was added to achieve slump values close to 0.

3.2. Phase II: Concrete Block Characterization

The optimized mixture design from the DOE method was used, considering an aggregate-to-cement ratio of 4.62 and a water-to-cement (W/C) ratio of 0.58 to achieve slump values close to 0. The high W/C ratio was due to the presence of silt and clay materials that have a larger surface area compared to sand and gravel, resulting in higher absorption power.

A total of nine concrete paving blocks were produced and tested following the specifications of the EN 1338 standard. In the following sections, the results related to the tests specified in the standard are presented.

3.2.1. Measurements

The consistency of the paving blocks was verified through geometrical measurements, making it a compulsory test based on Annex C of the EN 1338 standard. A total of nine blocks were produced and the measurements were recorded to the nearest millimeter. The dimensions, deviation, and permissible deviations are reported in Table 8. The obtained results indicate that the produced blocks were in line with the suggested requirements proposed by the standard. Therefore, the addition of silt to the concrete paving blocks did not have any adverse effects on the final produced materials in terms of geometrical properties. The standard also classifies the bricks based on their weight per square meter. The average value obtained for the concrete paving blocks was 121.04 kg/m^2, which is within the 120–180 kg/m^2 range noted for common concrete paving blocks.

Table 8. Concrete paving block average measurements and deviations.

Measurement	Length (mm)	Width (mm)	Height (mm)
Concrete blocks	200	100	60
Deviation	±1	±2	±2
Permissible deviation	±2	±2	±3

3.2.2. Water Absorption

Among the two methods defined by Annex E of the EN 1338 standard, the water absorption approach was selected to determine the weathering resistance of the paving blocks. The average data obtained for three samples regarding the water absorption are presented in Table 9.

Table 9. Average water absorption data and limits.

Paving Block	Water Absorption (%)
Concrete block	7.78 ± 1
EN 1338 limit	<6% (class 1-Mark B)

This test is of paramount importance for paving blocks to be used in pedestrian areas. Since the porosity of a material is directly responsible for its saturation level, the water absorption test could indirectly provide insight into the air-void content of the paving blocks. The standard suggests values lower than 6% for moisture content, whereas the concrete paving blocks showed a water absorption rate of 7.78%. Since no pressure was applied during the paving-block production, lower compaction rates were obtained. Studies have provided different methods for decreasing the water absorption of silt, such as applying pressure and vibration at high frequencies [30] or by adding lime to concrete mixtures [31].

3.2.3. Tensile Splitting Strength

The only mechanical test specified by the EN 1338 standard is the tensile splitting strength test. Table 10 presents the obtained average value of T and failure load (F) for three identical concrete paving-block samples. The standard states that the obtained values should not be lower than 3.6 MPa and 250 N/mm, respectively. None of the paving blocks reached such requirements. The average of the three samples tested equaled 1.7 MPa, which is about half of the required strength. Applying pressure during molding of the samples will most likely increase the final strength of the samples. Furthermore, the amount of water used to produce the paving blocks containing silt was higher than the normal water-to-cement ratios of common paving blocks. Thus, water could have limited the compaction rate, resulting in a low tensile splitting strength for the samples.

Table 10. Tensile splitting strength of concrete paving blocks after 28 days.

Paving Block	T(MPa)	F (N/mm)
Concrete block	1.7 ± 0.2	183.83 ± 3.0
EN 1338 limit	>3.6	>250

Moreover, the adopted casting method could be responsible for the formation of air voids, suggested by the high water absorption and low mechanical properties. The adoption of vibration at high frequencies and pressure during the molding procedure could decrease the porosity of the material, improving both properties.

3.2.4. Abrasion Resistance

The ability to withstand friction is defined as the abrasion resistance of a surface, which correlates directly to its durability. The wide wheel abrasion test was used to evaluate the abrasion resistance of the paving blocks based on the EN 1338 standard (Figure 8).

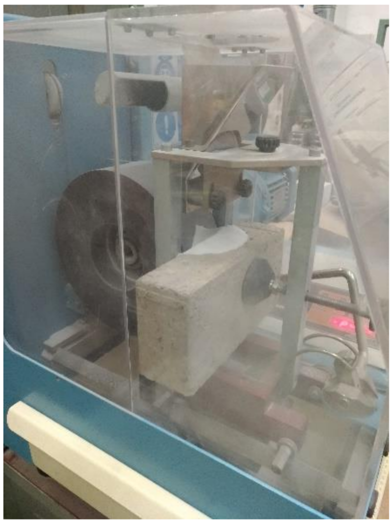

Figure 8. Wide wheel abrasion test on concrete paving blocks.

The obtained results and classification of the bricks are provided in Table 11. The average of three experimental bricks had an abrasion of 25.48 mm, classifying the bricks as Class 1-Mark F based on the standard. The curing conditions, mix design, and final surface of the paving blocks can directly affect the abrasion value [7]. Thus, improved resistance in terms of abrasion could be achieved through better curing of the bricks or by the inclusion of various materials such as waste rubber [32,33].

Table 11. Abrasion resistance for the concrete paving blocks.

Paving Block	Groove Dimension (mm)	Classification (EN 1338)
1	26.26	-
2	24.27	-
3	25.90	-
Average	25.48	Class 1-Mark F

3.2.5. Skid Resistance

The safety of pedestrians is an important parameter that should be considered during the production of paving blocks. One of the most important functional characteristics could be the unpolished slip-resistance value (USRV), as indicated in Annex I of the EN

1338 standard. The USRV indicates the suitability of paving blocks' finishing surface for pedestrians. The USRV of three identical paving blocks is shown in Table 12. The concrete paving blocks showed considerable skid resistance and fell within the lower and upper limits suggested by some guidelines. However, no limitations or suggestions are given by the EN 1338 standard. The inclusion of silt did not affect the slip/skid resistance of the material and the produced concrete paving blocks showed acceptable USRV values.

Table 12. Skid resistance of paving blocks.

Paving Block	USRV
1	73.4
2	71.4
3	72.2
Average	72.3

4. Conclusions

A Design of Experiments (mixture design) was applied to investigate the feasibility of including waste silt in concrete paving blocks. Based on the DOE, a total of 12 different aggregate blends consisting of gravel, sand, and silt were produced. Each of the 12 blends were tested for tensile splitting strength based on the EN 1338 standard. The produced model was then optimized using JMP software, resulting in the final blend having 15% gravel, 65% sand, and 20% of silt. The second phase of the study focused on the physical and mechanical properties of the concrete paving blocks produced with the optimized mix design. Based on the EN 1338 standard, shape and dimension measurements and various tests, including weathering resistance in terms of water absorption, tensile splitting strength, abrasion resistance, and slip/skid resistance, were conducted. The summary of the findings are as follows:

- The DOE method proved to be suitable for mixture optimization of the experimental concrete paving blocks.
- The samples produced with the optimum mixture showed consistency in terms of physical measurements, implying that the addition of silt did not negatively affect the workability of the concrete.
- The water absorption of the paving blocks was calculated as 7.78%, which is higher than the recommended values. This phenomenon could be related to the casting procedures, which allowed the formation of water-accessible voids.
- The recorded T values were lower compared to the required values for paving blocks.
- In terms of abrasion resistance, the experimental paving blocks fell in the lowest class foreseen in the EN 1338 standard. Improved curing methods or including specific materials in the mix design could improve the performance of the concrete blocks.
- The skid resistance fell within the recommended range, showing sufficient friction. This will assure the safety of pedestrians.

All in all, this preliminary laboratory characterization showed promising results to produce concrete paving blocks containing waste silt. However, improvements are needed to validate the application of this experimental material for the construction of paving areas.

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