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The computer program Tailings-DEM™ modeling the strength properties of Musselwhite tailings matrices

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Abstract. Mine tailings are the waste materials from mining operations. They are traditionally stored in tailings ponds that have been the subject of several environmental catastrophes that resulted in the contamination of the environment and underground water resources. This paper presents the development of a numerical tool, called Tailings-DEM, for simulating the unconfined compressive strength of Musselwhite tailings, which are sandy materials. This tool is developed based on the Discrete Element Method and the programming language C++. It is shown here that Tailings-DEM™ can be utilized to model Musselwhite tailings matrices and sands with a particle size distribution close to Musselwhite tailings. Additionally, it can be used to model demolition waste, coal mine refuse and Chat.

1. Introduction

Mine tailings are the waste materials that remain after the extraction of the ore mineral. They are traditionally stored in tailings ponds located in the vicinity of the mine opening [1]. This method of storage has created several environmental catastrophes in the past and has prevented the use of a widely available resource.

In order to make use of mine tailings and reduce their bulky method of storage [2] proposed the thickened tailings disposal (TTD) procedure for the disposal of mine tailings. He showed that by the process of thickening the tailings to heavy slurry before disposal, it is possible to create a self-supporting deposit of tailings and to eliminate the traditionally used settling pond.

The thickened surface tailings disposal concept has been applied at various mining facilities for several decades, including the Kidd Creek Mine in the northern region of Ontario (Canada) and for managing the disposal of red muds produced by the alumina industry [3].

Success in the process and results of mine tailings hardening led researchers to further investigate the possibility of using these hardened tailings in the construction industry thereby utilizing a vastly available...
untapped resource and hindering, albeit to a certain extent, the harmful effects of unprocessed tailings on the living environment. This success supported by historical evidence that told of using tailings in the mine backfilling business further strengthened this new approach.

The earliest reported use of mine tailings as a construction material was its use as a mine backfill material. Use of mine tailings for backfilling started in the early years of the potash industry by using dry and wet residues [4]. Several technologies were developed in the last 80 years. One of these, the slurry backfill technology is considered a very effective backfill method, because of its combination of tailings and brine disposal. Since 1908, the slurry backfill technology has been successfully applied in the German potash industry [4]. Success in these early attempts led researchers to attempt a thorough investigation approach of mine backfilling using more advanced technologies and procedures.

Several research studies discussed the applicability of using mine tailings in several types of construction applications. Examples include the works of Fall et al. [5], Fall et al. [6], Benzaazoua et al. [7], Yang et al. [8], Roy at al. [9], Ercikdi et al. [10], Fall and Pokharel [11], Helinski et al. [12], Ercikdi et al. [13], Ugama et al. [14] and Liu et al. [15]. However, none had comprehensively addressed the issue of using mine tailings as construction material for temporary roads in cold climates. Simulation of the strength and weathering characteristics of these tailings using a powerful numerical technique was lacking in these studies, as well.

The main objective of this study is the development of a new sustainable approach to road construction using mining waste in cold climate through the development of a Discrete Element Method (DEM) program as a tool for simulating the strength characteristics of the newly developed Musselwhite tailings-binder matrices.

Investigations consist of two phases: experimental and computational. The Experimental Phase 1 is divided to 3 stages: characteristics of materials, formulation of tailing matrices and assessment of matrices usefulness as a road construction material. The Experimental Phase is thoroughly discussed in Mahmood [16]. Phase 2 consists of 3 stages: development of an adequate program predicting matrices usefulness for road material and verification of the program for strength and weathering tests. This paper discusses the verification of the strength tests for Musselwhite tailings matrices as verification for weathering tests was discussed elsewhere [16].

2. Binding materials

The binding materials for the mine tailings, which have been tested in this study, consist of Type I ordinary Portland cement (OPC), fly ash, slag and Calsifrit.

Unconfined compressive strength of fly ash lies in the range 1.38 to 6.895 MPa with permeability between $10^{-5}$ to $10^{-9}$ cm/s [17]. The fly ash was obtained from St. Laurence Cement Company in Longueil, Quebec.

Ground granulated blast furnace slag used in this study was obtained from Lafarge North America Cement Company in Montreal, Quebec under the trade name NewCem®. It is a light grey odorless powder produced in accordance with ASTM C 989 [18]. It is composed of (30-50) % Calcium Oxide, (0-20) % Magnesium Oxide with less than 1% Crystalline Silica. Its specific gravity is between 2-3, water pH 8-11. Its boiling point is above 1000 °C [19].

Calsifrit™ is a totally amorphous siliceous material, a matrix of calcium and sodium fluoro-aluminosilicate. This homogeneous solid substance has a blackish grey color, possesses a high reactivity potential and shows cementitious properties when finely ground. This product was obtained from the manufacturer NovaFrit International. Table 4 shows its chemical composition. Calsifrit has a pH (1% solution in water) of 6.5-7.5, a melting point of 800 °C, a specific gravity of 1.3 with a moisture content of less than 10% [20].

3. The tailings
Musselwhite tailings have a specific gravity of 3.26 and their physical properties are shown in Table 1. Atomic absorption analysis performed on the tailings revealed that the tailings contained heavy metals in the following proportions (mg/kg): Cu (144), Fe (87200), Cr (67), Zn (36), Pb (180).

Table 1. Physical properties of Musselwhite tailings

| Type of Tailings | Musselwhite |
|------------------|-------------|
| $D_{10}$ (mm)    | 0.0045      |
| $D_{50}$ (mm)    | 0.016       |
| $D_{60}$ (mm)    | 0.023       |
| $D_{30}$ (mm)    | 0.012       |
| $C_u$            | 5           |
| $C_z$            | 1.39        |
| $P_{4.75\text{mm}}$ (%) | 100       |
| $P_{0.075\text{mm}}$ (%) | 74.9      |
| Initial moisture content (%) | 30.15 |
| USCS             | SM          |

Where:
$D_{10} =$ diameter corresponding to 10% finer,
$D_{50} =$ diameter corresponding to 50% finer,
$D_{60} =$ diameter corresponding to 60% finer,
$D_{30} =$ diameter corresponding to 30% finer,
$C_u =$ uniformity coefficient = $D_{60}/D_{10}$,
$C_z =$ coefficient of gradation = $D_{30}^2/(D_{10}D_{60})$,
$P_{4.75\text{mm}}$ (%) = percentage passing sieve no.4,
$P_{0.075\text{mm}}$ (%) = percentage passing ASTM sieve # 200,
SW-SM = well graded sand with silt,
SM = silty sand,
SP = poorly graded sand,
USCS [21] = unified soil classification system.
4. Preparation of cylindrical specimens

Cylindrical specimens of tailings matrices with dimensions (44 diameter x 74 height) mm were molded for this purpose in accordance with ASTM D 4842 [22]. These cylindrical specimens were, then, left to cure in the moisture chamber for 28 days in the case of the wetting and drying samples, and for 43 days for the freezing and thawing. Unconfined compression tests were conducted on these tailings matrices after subjecting them to 12 cycles of drying at 60 °C and wetting by being submerged in distilled water at room temperature. The remaining samples were compressed after 12 cycles of freezing at -20 °C in a freezing cabinet and thawing in distilled water at room temperature (22 °C). Table 2 shows the codes used for the cylindrical specimens of the tailings matrices. Speed of descent of the platen was kept constant at 70 mm/min. Details of the wetting/drying and freezing/thawing weathering resistance tests are further explained in Mahmood [16].

| Tailings Type | Weathering Type | Code | Specimen | Binder/Tailings (%) | OPC/Binder (%) | Calsifrit/Binder (%) | Flyash/Binder (%) | Slag/Binder (%) |
|---------------|----------------|------|----------|---------------------|----------------|---------------------|------------------|-----------------|
| Musselwhite   | Wetting/Drying | MW1  | 1, 2, 3, 4, 5, 6 | 0.375 | 100 | 0 | 0 | 0 |
|               |                | MW3  | 1, 2, 3, 4, 5, 6 | 0.375 | 90 | 10 | 0 | 0 |
|               |                | MW6  | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 25 | 0 | 0 |
|               |                | MWF1 | 2, 3, 4, 5, 6   | 0.375 | 75 | 0 | 25 | 0 |
|               |                | MWF2 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 10 | 15 | 0 |
|               |                | MWF3 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 20 | 5 | 0 |
|               |                | MWS1 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 0 | 0 | 25 |
|               |                | MWS2 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 10 | 0 | 15 |
|               |                | MWS3 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 20 | 0 | 5 |
| Musselwhite   | Freezing/Thawing | MW1  | 1, 2, 3, 4, 5, 6 | 0.375 | 100 | 0 | 0 | 0 |
|               |                | MW3  | 1, 2, 3, 4, 5, 6 | 0.375 | 90 | 10 | 0 | 0 |
|               |                | MW6  | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 25 | 0 | 0 |
|               |                | MWF1 | 2, 3, 4, 5, 6   | 0.375 | 75 | 0 | 25 | 0 |
|               |                | MWF2 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 10 | 15 | 0 |
|               |                | MWF3 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 20 | 5 | 0 |
|               |                | MWS1 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 0 | 0 | 25 |
|               |                | MWS2 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 10 | 0 | 15 |
|               |                | MWS3 | 1, 2, 3, 4, 5, 6 | 0.375 | 75 | 20 | 0 | 5 |
5. Execution and verification of Tailings-DEM™ modeling of UCS

In order to operate, the program Tailings-DEM™ uses a parameter called the matrix mass coefficient. It is computed through the following steps:

1) The unconfined compressive stress is found from the statistical predictive equation derived previously in Mahmood [16]. The UCS was found by entering the following matrix components (in percentage): Calsifrit/binder (A), slag/binder (C) and binder/tailings (E) into Equation (1) as follows:

\[ UCS = -6.856 + 0.14A + 0.092C + 0.6198E \quad (1) \]

From the UCS above, it is possible to find the maximum compressive force (in N) for each of the matrix mixtures used in this equation.

2) Subsequently, the maximum load (in N) found experimentally [16] for the same mixtures used in step (1) above, is used to find a correlation with a factor defined as the matrix mass coefficient. This correlation is found by initially taking three values of the experimental maximum load and finding (by trial and error) their representative matrix mass coefficients (in kg) that gives the closest match with the computational values. The three values represent the maximum and minimum data boundary shown in Figure 1 and an arbitrary middle point. Subsequently other values for the matrix mass coefficient are introduced into the program to find the closest match with the remaining experimental values. This procedure generated the following linear Equation (2) shown in Figure 1 that relates the experimental maximum load and the matrix mass coefficient:

\[ y = 2 \times 10^6 x - 276.9 \quad (2) \]

Where: \( y \) is the experimental maximum load (in N) and \( x \) is the matrix mass coefficient (in kg).

The matrix mass coefficient is the major input used in the computer program to find the computational values including the computational maximum force for each tailings matrix mixture.
3) The computational maximum force values were produced in step (2) as a byproduct of using the matrix mass coefficient. Hence, the same matrix mass coefficient now represents these new computational maximum force values and their corresponding experimental counterparts. Using regression techniques produced Equation (3) shown in Figure 2, that relates the newly found computational maximum forces and their respective matrix mass coefficients:

\[ y = 2 \times 10^9 x + 39.27 \]  

(3)

Where: \( y \) is the computational maximum load (in N) and \( x \) is the matrix mass coefficient (in kg).

4) Equation (3) is used to find the matrix mass coefficient when the statistical UCS value is found from Equation (1). This matrix mass coefficient is the major input used in the computer program to get the corresponding computational maximum force value.

5) Computational maximum force values found in step (4) are then compared with their experimental counterparts.

Table 3 shows the values generated from the procedure explained in steps 1 to 5.

Figure 2 shows the correlation between values of the experimental and computational maximum loads [16] found using the procedure explained above.
Subsequently, the user is prompted to enter the time increment in seconds. This time increment is part of the original stress and strain equations [16]. Equation (4) checks for its compatibility with the value $\sqrt{m/k}$. If the time increment is more than or equals the latter value, the user is asked to re-enter the time increment until compatibility is assured. Figure 3 shows the correlation between the experimental and numerical maximum loads.

\[ \Delta t < 2 \times \frac{\sqrt{m}}{k} \]  (4)
Correlation between the experimental maximum load vs. the Tailings-DEM maximum load

Subsequent to the input operations, triangular particles, that represent the divisions, are arranged in a grid like fashion and dispersed uniformly throughout a rectangular area that represents the cylinder under compression.

Table 3. Numerical procedure used in calculating the matrix mass coefficient

| Stat. Max. (N) | Eq. load (Eq. from (5.15)) | Weight (kg) | Max. Load from Program Run (N) | Difference (%) | Exp. Load (N) | Max Load (N) | Difference (%) |
|---------------|-----------------------------|-------------|---------------------------------|----------------|--------------|--------------|----------------|
| 36696.49      | 1.84E-05                    | 35200       | 37146.57                        | 5.24           |              |              |                |
| 38825.24      | 1.94E-05                    | 37300       | 39001.62                        | 4.36           |              |              |                |
| 42018.35      | 2.1E-05                     | 40400       | 38378.2                         | -5.27          |              |              |                |
| 36696.49      | 1.83E-05                    | 35200       | 34926.59                        | -0.78          |              |              |                |
| 38825.24      | 1.94E-05                    | 37300       | 39868.32                        | 6.44           |              |              |                |
| 40953.98      | 2.05E-05                    | 40400       | 39275.31                        | -2.86          |              |              |                |
| 40193.71      | 2.01E-05                    | 38500       | 43517.59                        | 11.53          |              |              |                |
| 40923.57      | 2.04E-05                    | 38500       | 42422.81                        | 9.25           |              |              |                |
| 41653.42      | 2.08E-05                    | 40400       | 44810.04                        | 9.84           |              |              |                |
| 24916.18      | 1.24E-05                    | 23900       | 20527.17                        | -16.43         |              |              |                |
| 27044.92      | 1.35E-05                    | 26000       | 24951.91                        | -4.20          |              |              |                |
After the particles arrangement, the program loading loop starts with increments of 100 N. It is thought that this increment furnishes sufficient data points for graph plotting and data manipulation. At the start of loading, the rectangular area gets divided into 16 sectors equal in area to facilitate contact detection among the particles. A counter for each sector stores the number of particles dispersed in it. Then execution moves to the first sector to check for contact detection among particles. The first sector particle is taken and checked for contact with other particles. Once contact is found, its contact meter is increased by one up to a maximum of 4 contact points with 4 other particles. It is thought that the limiting geometry of these triangles does not permit interaction with more than 4 particles without encountering serious computational errors. Equation (5) shows the numerical condition that checks for contact among neighboring particles. Initial trials have shown that this is the minimum distance possible to achieve reasonable results.

\[(x_1 - x_i)^2 + (y_1 - y_i)^2 \leq 50 \text{ mm}\]  \hspace{1cm} (5)

Where:
- \(x_1, y_1\) are the Cartesian coordinates of the particle under consideration, and
- \(x_i, y_i\) are the coordinates of the particle to be checked for contact proximity

This contact is the mechanism that activates stresses and strains [16]. After checking the first particle for contact, the sector particle counter is increased and the procedure repeated for the remaining sector particles.

Then execution moves from the first sector to the second sector and the whole contact procedure is repeated again until all sectors are checked. After that, execution moves to the loading stage again and
another increment of 100 N is applied. This continues until a displacement of 72 mm in the vertical
direction is reached. This displacement is scaled by 10 to account for the differences in the experimental
and computational modeling and to account for the 2-dimensional approximation. When this
displacement is reached, the specimen failure is assumed to take place and the program stops. As such,
the program is capable of finding x, y stresses and strains for its member particles.

6. Computational and experimental results

It is necessary to verify the accuracy and reliability of the proposed computational model using
laboratory-approved experimental results. Hence the UCS results of Mahmood [16] were used in the
verification and analysis of the computational data found using this computational program.

It is known that solidified waste in the field undergoes continuous weathering cycles. Therefore,
strength testing will not be complete without investigating the effect of weathering cycles on the
compression UCS strength.

After undergoing the weathering tests, the matrices specimens of tailings were tested under uniform
conditions to find their strength in the UCS apparatus. Figures 4 to 8 show the UCS experimental and
computational results comparison for Musselwhite tailings matrices for the matrix binder combinations
shown above. The experimental specimens had been subjected to freezing/thawing weathering cycles
before undergoing the UCS compression testing. The following shows these matrix binder combinations
in groups of figures:

1) Figure 4 shows the 100% OPC,
2) Figure 5 shows the 90% OPC, 10% Calsifrit,
3) Figure 6 shows the 75% OPC with 25% Calsifrit,
4) Figure 7 shows the 75% OPC with 25% fly ash,
Figure 4. Computational and experimental UCS values for Musselwhite samples MW’11(a)-MW’16(b) after freezing/thawing.
Figure 5. Computational and experimental UCS values for Musselwhite samples MW’31(a)-MW’36(b) after freezing/thawing.
Figure 6. Computational and experimental UCS values for Musselwhite samples MW’61(a)-MW’66(b) after freezing/thawing.
Figure 7. Computational and experimental UCS values for Musselwhite samples MWF’11(a)-MWF’16(b) after freezing/thawing.
7. Discussion of Tailings-DEM™ strength modeling

Experimental and computational UCS values for the tailings matrices have similar types of curves indicating that computational modeling of this test was to a large extent accurate. Marginal differences between experimental and computational values could be attributed to a few factors.

The main difference between the computational and the experimental programs is the approximation to 2D modeling when designing this program. Also, binder constituents were largely modeled through the UCS in Equation (1), which was derived statistically. As explained in Mahmood [16], this equation found, out of the four binders used, the ratio of Calsifrit and slag to be most effective when calculating the UCS. The effect of cement could not be associated directly with the UCS. Its effect, however, was evident in conjunction with the other combinations, specifically, the binder/tailings ratio. Also, the experimental tests used a constant platen speed that was not modeled in the computational program.

The computer program is capable of modeling other types of wastes and binders. The matrix mass coefficient shown above can be used with other types of wastes. By first finding the experimental UCS for the waste matrix in question, the matrix mass coefficient can be incorporated into the program and used as detailed above.

Generally, the computational data followed experimental results closely for these tailings matrices for the cases shown. Maximum values and slopes for the experimental and computational results followed closely. However, the freezing/thawing specimens have higher slopes for the same tailings matrices indicating the move from ductile to more brittle behavior.

The marginal differences between the computational and experimental UCS results could be attributed to the experimental errors in preparing the specimens tested. It is known that soil cement matrices suffer from result variability as explained in Mahmood [16]. Furthermore, the presence of the metals; Fe, Zn and Pb in Musselwhite matrices have further complicated the outcome of the UCS experiments.

As water and cement are added to Musselwhite tailings, zinc hydroxide anions form and compete effectively with other anions for available adsorption sites to form a low permeability membrane coating the cement particles [23]. Several researchers reported that Zn retarded setting through formation of this low permeability membrane of calcium hydroxyzincate (CaZn$_2$(OH)$_6$.H$_2$O) around the cement particles [23], [24], [25],[26], and Pb acted as a retardant agent by inhibiting the cement hydration [27]. The formation of a membrane around cement particles with the precipitation of calcium hydroxyzincate (CaZn$_2$(OH)$_6$.H$_2$O) can prevent water and ion transport needed for cement hydration. The retardation or suppression of cement hydration adversely affects strength development. In the presence of lead, hydration occurs at a much slower rate than the reference [27], and the UCS values tend to decrease. Coating of tri-calcium silicate 3CaO.SiO$_2$ (C$_3$S) of cement with Pb or complexation of Pb [25], [28], [29] might have retarded the hydration of cement.

The initial water content of the samples might have also been a contributing factor to the decrease in the UCS values. The initial water content of 30.15% for Musselwhite plus the water/cement ratio of 3/10 might have been excessive for cement hydration especially as the Calsifrit ratio of the samples increased. Visual observation during the experiments revealed that increasing the amount of Calsifrit increased the fluidity of these mixes. Conner [17]reported that as the water/cement ratio increased, the percentage of larger pores and therefore the permeability of the product increased, as well. These experimental results were used in the multiple regression analysis that led to the creation of predictive Equation (1).

Another reason could be the assumptions used in defining the program Tailings-DEM™. The assumptions were based on assuming the particles being right-isosceles triangles. This assumption had affected the other assumption of contact mechanism as was above. In reality, however, soil particles have varying shapes and smaller sizes and their contact mechanism is much more complicated and varied. In addition, most soils contain different amounts of humidity, an affect that was not modeled in Tailings-DEM™.

8. Tailings-DEM™ applications
Since Musselwhite tailings were predominantly sandy, Tailings-DEM™ can be incorporated to model other types of aggregates, such as sands and gravely sands. This program can be utilized to model sands with a particle size distribution close to Musselwhite tailings.

Tailings-DEM™ can be applied to the following types of waste materials:
1) Demolition waste,
2) Coal mine refuse,
3) Chat.

8.1 Demolition waste

The Ministry of Industry in Canada defines the construction and demolition waste as “waste materials from the construction and demolition of roads, bridges and buildings such as wood gypsum and metal”, [30]. Hence most tailings components are common with demolition waste.

Construction and demolition debris are one of the most abundant types of man-made wastes found in Canada. For example in Alberta, construction and demolition waste accounts for about 25% of the total amount of municipal solid waste sent to landfills [31].

Compressive strengths for construction and demolition debris cubes at the age of 28 days range from 11.05 to 28.25 MPa [32]. This makes them structurally close, in terms of strength, to the Musselwhite tailings modeled in this study.

The matrix mass coefficient for the construction and demolition debris samples can be obtained from these studies and used in this computer program along with the stiffness coefficient. The same study produced experimental values of the modulus of elasticity [32]. These values can be substituted for the stiffness coefficient as the first input to the program.

8.2 Coal mine refuse

Coal refuse is a by-product of the coal mining industry. Coal refuse is, generally, defined by a minimum ash content combined with a maximum heating value measured on a dry basis [33]. This material consists primarily of non-combustible rock with some attached carbon material that cannot be effectively separated [33].

Coal continues to be one of the primary sources of energy in several countries including the United States where mining of coal results in the production of large quantities of coal refuse. It is estimated that over 500 million tons of coal mining and preparations refuse are produced annually in the United States [34]. Cementation and stabilization of coal mine refuse for proper re-use in construction applications removes most of the harmful environmental effects resulting from land filling.

Kumar et al. [34] report that several studies have been conducted with the purpose of investigating the use of stabilized and un-stabilized mixtures of coal mine refuse and fly ash, considered as the two most important by-products of the coal industry, for construction of highway embankments and base courses [35], [36], [37], [38], [39], [40].

The matrix mass coefficient can be produced from the compressive strength of coal refuse mixtures. Crandall [41] reports that Knissel and Helms [42] provided values of uniaxial compressive strength of coal mine washery refuse samples of up to 4 MPa. These values were the result of 28 days curing with a ratio of 10% cement [41].

The matrix mass coefficient defined in this study can be successfully used with cement stabilized coal mine refuse, after experimentally finding the proper UCS values and stiffness coefficients as detailed above.

8.3 Chat
Mine tailing piles (chat) are comprised mainly of angular chert fragments and contain residual amounts of lead sulfide (galena), zinc sulfide (sphalerite) minerals and their weathering products [43]. The difference between chat and tailings material is that chat is a fine to coarse dolomite produced during the early milling process, which used density separation [44]. Chat is transported mechanically by conveyor and deposited in large piles. Tailings are produced in later years using a wet chemical process and have typically smaller fragments than chat [44]. The tailings are hydraulically deposited into impoundments known as tailings ponds [45].

Chat has been used for the stabilization of roadway bases with additives such as fly ash and cement kiln dust for stabilization and solidification purposes [46].

An experimental study by Wasiuddin et al. [46] to optimize the use of chat in hot mix asphalt for pavement application showed great potential in the use of chat for both surface and base course layers.

Teredesai et al. [47] reported UCS values of up to 5.2 MPa for cylindrical specimens of chat stabilized with class C fly ash and cement kiln dust and cured for 28 days.

The matrix mass coefficient can be used in conjunction with chat mechanical properties to optimize the use of chat with other binders and determine its suitability for construction purposes. Higher binder content may need to be used with angular chat fragments.

9. Conclusions

- A novel numerical tool was developed to model the strength characteristics of tailings matrices. The tool was designed using the compiler Code Blocks and the computer programming language C++,
- The DEM tool developed (Tailings-DEM™) is capable of simulating, with great accuracy, the UCS strength values of the Musselwhite tailings matrices tested,
- Since Musselwhite tailings were predominantly sandy, the program can be incorporated to model other types of aggregates, such as sands and gravelly sands. Tailings-DEM™ can be utilized to model sands with a particle size distribution close to Musselwhite tailings. Additionally, it can be used to model demolition waste, coal mine refuse and Chat.

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