

APPARATUS AND METHOD FOR CONCRETE ADDITIVE MANUFACTURING

The present application claims priority from the Singapore patent application no. 10202012256X, the contents of which are incorporated herein in entirety by reference.

TECHNICAL FIELD

[0001] The present disclosure relates to the field of additive manufacturing, and more particularly to concrete additive manufacturing.

BACKGROUND

[0002] Extrusion-based 3D concrete printing (3DCP) or concrete additive manufacturing refers to the building of a structure by extruding materials layer-atop-layer through a nozzle. One of the main benefits of the 3DCP technology is that it can perform formwork-free concrete construction with enhanced design freedom without additional labor and cost. In comparison to precast prefabrication of a structural unit, such as a prefabricated bathroom unit, concrete additive manufacturing advantageously enables smaller batches to be fabricated economically and has greater flexibility for customization. One hurdle to broader applications of 3DCP in the construction sector however is the need to improve the structural integrity of end products.

SUMMARY

[0003] In one aspect, the present disclosure provides an apparatus for concrete additive manufacturing, the apparatus comprising: a housing coupleable to an actuator, the housing defining: a main nozzle defining a main axis, the main nozzle being configured to extrude a flowable concrete material to form a concrete extrudate; and a first peripheral nozzle disposed adjacent to the main nozzle, the first peripheral nozzle configured to extrude a first bonding agent to form a first bonding agent extrudate, wherein the housing is configured to be moveable by the actuator to undergo a movement along a curvilinear printing path, wherein the movement includes a translational movement concurrent with a rotational movement about the main axis.

[0004] The apparatus as described above, wherein the first peripheral nozzle and the main

nozzle are configured to undergo the rotational movement about the main axis as a rigid body.

[0005] The apparatus according to any described above, wherein the first peripheral nozzle is coupled to the main nozzle at one of a leading side and a trailing side of the main nozzle.

[0006] The apparatus according to any described above, wherein the first bonding agent is a viscous material.

[0007] The apparatus according to any described above, wherein the apparatus is configured to selectively: deposit the concrete extrudate ahead of depositing the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a first configuration; or deposit the concrete extrudate behind that of laying the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a second configuration.

[0008] The apparatus according to any described above, wherein the first bonding agent extrudate has a width smaller or equal to a width of the concrete material extrudate. The apparatus according to any described above, wherein the first bonding agent extrudate is formed substantially in line with the printing path. The apparatus according to any described above, wherein the first bonding agent extrudate is deposited parallel to the printing path.

[0009] The apparatus according to any described above, wherein the main nozzle is configured with a polygonal outlet. The apparatus according to any described above, wherein the polygonal outlet is a rectangular outlet.

[0010] The apparatus according to any described above, wherein the housing is configured to be rotatably coupleable to the actuator, wherein the apparatus is rotatable about the main axis.

[0011] The apparatus according to any described above, further comprising a first spreader disposed adjacent to the first peripheral nozzle, wherein the first spreader is configured to redistribute the first bonding agent extrudate. The apparatus according to any described above, wherein the first bonding agent extrudate is spread on a selected surface of the concrete extrudate. The apparatus according to any described above, wherein the main

nozzle and the first spreader are disposed on opposing sides of the first peripheral nozzle. The apparatus according to any described above, wherein the main nozzle and the first peripheral nozzle are disposed on opposing sides of the first spreader.

[0012] The apparatus according to any described above, wherein the housing further defines a main channel in fluid communication with the main nozzle, the main channel being configured to receive the flowable concrete material from a concrete source. The apparatus according to any described above, wherein the housing further defines a first peripheral channel in fluid communication with the first peripheral nozzle, the first peripheral channel being configured to receive the first bonding agent from a first bonding agent source. The apparatus according to any described above, wherein the first peripheral channel is configured as a funnel, the first peripheral channel includes a receiving opening substantially larger than the first peripheral nozzle.

[0013] The apparatus according to any described above, further comprising a flow splitter, the flow splitter being in fluid communication with the first bonding agent source, the flow splitter having at least two flow outlets, wherein the at least two flow outlets are configured to direct the first bonding agent from a first bonding agent source into respective distinct regions of the receiving opening of the first peripheral channel. The apparatus according to any described above, wherein the distinct regions of the receiving opening are diametrically disposed about the main axis.

[0014] The apparatus according to any described above, wherein the first peripheral channel is sealingly connected to the first bonding agent source to form a pressurized chamber in the first peripheral channel.

[0015] The apparatus according to any described above, wherein the housing further defines a second peripheral nozzle configured to extrude a second bonding agent as a second bonding agent extrudate, wherein the second peripheral nozzle and the first peripheral nozzle are disposed on opposing sides of the main nozzle in line with the printing path. The apparatus according to any described above, further comprising a second spreader disposed adjacent to the second peripheral nozzle, wherein the second spreader is configured to redistribute the second bonding agent extrudate. The apparatus according to any described above, wherein the housing further defines a second peripheral channel, the second

peripheral channel being in fluid communication with the second peripheral nozzle, and wherein the second peripheral channel is configured to receive a second bonding agent from a second bonding agent source.

[0016] The apparatus according to any described above, wherein the second bonding agent is characterized by a different composition from the first bonding agent.

[0017] In another aspect, a system for concrete additive manufacturing comprises: the apparatus according to any described above; an actuator coupled to the apparatus; and an actuator controller configured to control the actuator to move the apparatus along the printing path to lay the concrete extrudate and the first bonding agent extrudate.

[0018] The system according to any described above, wherein the actuator controller is configured to control the actuator to rotate the apparatus along a curved portion of the curvilinear printing path.

[0019] The system according to any described above, wherein at least one of the bonding agents is a viscous material.

[0020] The system according to any described above, wherein at least one of the bonding agents is a cement paste with a 0.26 water-to-cement ratio.

[0021] The system according to any described above, wherein the at least one of the bonding agents comprises a superplasticizer.

[0022] In another aspect, the present document discloses a method of concrete additive manufacturing, the method comprising: extruding a flowable concrete material via a main nozzle to form a concrete extrudate, the main nozzle defining a main axis; extruding a first bonding agent via a first peripheral nozzle to form a first bonding agent extrudate; and providing a movement of the main nozzle and the first peripheral nozzle along a curvilinear printing path, wherein the movement includes a translational movement concurrent with a rotational movement about the main axis, and wherein the movement is concurrent with the extruding of the flowable concrete material and the extrusion of the first bonding agent.

[0023] The method according to any described above, wherein the first peripheral nozzle

and the main nozzle are configured to undergo the rotational movement about the main axis as a rigid body.

[0024] The method according to any described above, wherein the first bonding agent is a viscous material.

[0025] The method according to any described above, the method comprising one of: depositing the concrete extrudate ahead of depositing the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a first configuration; and depositing the concrete extrudate behind that of laying the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a second configuration.

[0026] The method according to any described above, wherein the first bonding agent extrudate is deposited parallel to the concrete extrudate, the concrete extrudate being extruded via a rectangular outlet of the main nozzle.

[0027] The method according to any described above, further comprising: spreading the first bonding agent extrudate on a selected surface of the concrete extrudate.

[0028] The method according to any described above, wherein the first bonding agent is spread concurrently with the movement of the main nozzle and the first peripheral nozzle.

BRIEF DESCRIPTION OF DRAWINGS

[0029] Fig. 1 is a schematic diagram of a system for concrete additive manufacturing according to an embodiment of the present disclosure;

[0030] Fig. 2 is an example of a concrete structure 3D printed by the system of Fig. 1;

[0031] Fig. 3A is an isometric view of an apparatus according to an embodiment of the present disclosure;

[0032] Fig. 3B is a sectional view of the apparatus of Fig. 3A

[0033] Fig. 4A is a side view of the apparatus of Fig. 3A in a first configuration;

[0034] Fig. 4B is a side view of the apparatus of Fig. 3A in a second configuration;

[0035] Fig. 5 is a sectional view of the apparatus of Fig. 3A;

[0036] Fig. 6 is a top isometric view of the apparatus of Fig. 3A;

[0037] Fig. 7A is a top view of a curved portion of a printing path according to an embodiment;

[0038] Fig. 7B shows a sectional view of a rectangular concrete extrudate according to Fig. 7A;

[0039] Fig. 7C is a top view of the apparatus at different positions of the curved portion of Fig. 7A;

[0040] Fig. 7D is a top view of the apparatus rotating between the first orientation and the second orientation;

[0041] Fig. 8 is a side view of an apparatus according to another embodiment of the present disclosure;

[0042] Fig. 9 is an isometric view of the apparatus according to one embodiment;

[0043] Fig. 10 is a detailed view of the apparatus according to another embodiment;

[0044] Fig. 11 is a side view of the apparatus of Fig. 10;

[0045] Fig. 12 is an isometric view of an apparatus according to yet another embodiment;

[0046] Fig. 13 is a detailed view of the apparatus of Fig. 12;

[0047] Fig. 14 is a side view of the apparatus of Fig. 12;

[0048] Figs. 15A and 15B are images of cross sections showing defects in a specimen of a printed structure;

[0049] Figs. 15C and 15D are images of cross sections of a specimen 3D printed using an embodiment of the present disclosure;

[0050] Fig. 16 is a plot of the relative bond strength of the printed structures of Figs. 15A

to 15D;

[0051] Fig. 17 is a sectional view of an apparatus according to another embodiment;

[0052] Fig. 18 is a side view of the apparatus of Fig. 17;

[0053] Fig. 19 is a sectional view of an apparatus according to yet another embodiment;

[0054] Fig. 20 is a side view of an apparatus according to Fig. 19; and

[0055] Fig. 21 is a schematic flow diagram of a method of concrete additive manufacturing according to the present disclosure.

DETAILED DESCRIPTION

[0056] Reference throughout this specification to “one embodiment”, “another embodiment” or “an embodiment” (or the like) means that a particular feature, structure, or characteristic described in connection with the embodiment is included in at least one embodiment. Thus, the appearance of the phrases “in one embodiment” or “in an embodiment” or the like in various places throughout this specification are not necessarily all referring to the same embodiment. Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. In the following description, numerous specific details are provided to give a thorough understanding of embodiments. One skilled in the relevant art will recognize, that the various embodiments be practiced without one or more of the specific details, or with other methods, components, materials, etc. In other instances, some or all known structures, materials, or operations may not be shown or described in detail to avoid obfuscation.

[0057] The word “exemplary” is used herein to mean “serving as an example, instance, or illustration.” Any embodiment described herein as “exemplary” is not necessarily to be construed as preferred or advantageous over other embodiments. As used herein, the singular ‘a’ and ‘an’ may be construed as including the plural “one or more” unless apparent from the context to be otherwise.

[0058] Terms such as “first” and “second” are used in the description and claims only for the sake of brevity and clarity, and do not necessarily imply a priority or order, unless

required by the context. The terms "about" and "approximately" as applied to a stated numeric value encompasses the exact value and a reasonable variance as will be understood by one of ordinary skill in the art, and the terms "generally" and "substantially" are to be understood in a similar manner, unless otherwise specified.

[0059] For the sake of brevity, the terms "3D concrete printing", "concrete additive manufacturing", "3D concrete manufacturing", "concrete additive printing", and "3D concrete printing" are used interchangeably. The terms "concrete extrudate", "concrete layer", "concrete extrudate layer", "concrete printing material", and "concrete deposit", etc. are used interchangeably. Similarly, terms "bonding agent extrudate", "bonding agent layer", "bonding agent material", and "bonding agent deposit", etc. are also used interchangeably.

[0060] In this disclosure, the term "extrude" or "extrusion" refers to the action or process of molten/semi-solid/solid material passing through an outlet of an apparatus to be shaped and formed as a continuous material with a generally uniform cross section. The terms "extrude", "deposit", "lay", "print", and "form" may be used interchangeably as the context will make clear. Similarly, "extrudate" refers to an end product of extrusion, namely, a continuous molten/semi-solid/solid material, of a viscosity enabling the material to be flowable and generally taking on a cross section or profile determined by the outlet of the nozzle/apparatus.

[0061] To aid understanding, the various embodiments of the present disclosure will refer to a concrete extrudate as the primary extrudate for use in fabricating a structure/building structure. However, it will be understood from the context that the present apparatus can similarly be used with other types of viscous materials. The term "viscous material" is used herein to describe materials that is flowable for use in 3D printing of large structural products (such as building units) and viscous enough to hold a pre-determined shape for the purpose of forming products requiring a certain degree of structural strength and integrity. A conventional apparatus designed to deliver a spray or jet of materials would therefore not be suitable for use with a viscous material as the viscous material will clog up the jet/spray outlet, in the context of the term "viscous material" as used herein.

[0062] Further, the terms "concrete printing material", "concrete material", "molten

concrete material”, and “flowable concrete material” as used herein refer to flowable cement or concrete material suitable for 3D concrete printing. Such flowable concrete material may encompass different materials of differing physical and chemical properties, such as differing viscosity, water content, expansion/contraction coefficients, thermal conductivity, etc. Upon the concrete printed material setting or hardening, the respective hardened concrete printed material may have differing physical and chemical properties (as compared to its flowable state). The concrete printed material may be described in terms of properties, such as but not limited to Young’s Modulus (E), strength, hardness, fracture toughness, Poisson ratio, etc., relative to the properties of the material prior to its setting or hardening.

[0063] The bonding agents disclosed herein may encompass different materials of different chemical compositions with differing physical and chemical properties. As an example, a bonding agent suitable for used with the present disclosure may be selected from a range of bonding agents having a large range of viscosity, ranging from low viscosity free flowing material to a high viscosity slow flowing material. Examples of bonding agents include, but are not limited to, water, cement strengthener, polymer solution, cement paste, etc.

[0064] Various embodiments of an apparatus for concrete additive manufacturing are disclosed. As shown in **Fig. 1**, disclosed is an embodiment of a system **100** for concrete additive manufacturing, for example 3DCP. For the sake of brevity and clarity, selected portions of the system **100** are shown and described in detail. The system **100** includes an apparatus **200**; an actuator **300** coupled to the apparatus **200**; and a pump system **400** in fluid communication with the apparatus **200**. The actuator **300** may be coupled to and controllable by an actuator controller **310**. The pump system **400** includes a concrete source **410**. The concrete source **410** may be coupled to a concrete pump **420** which is configured to provide a flowable concrete material to the apparatus **200**. The pump **400** may further include a first bonding agent source **430** coupled to a first bonding agent pump **440**. The first bonding agent pump **440** is configured to provide a first bonding agent to the apparatus **200**. One or more pump controller **490** is configured to control the concrete pump **420** and the first bonding agent pump **440**. In some embodiments, there is more than one bonding agent source and more than one respective bonding agent pump. The actuator controller **310** is configured to control the actuator **300** such that the apparatus **200** travels along a curvilinear printing path **80** to lay a concrete extrudate and a first bonding agent extrudate.

[0065] **Fig. 2** illustrates a concrete structure printable by the system **100** according to an example of a curvilinear printing path **80**. The printing path **80** may be configured as a closed loop. The printing path **80** may include straight portions **80a** and curved portions **80b**. The printing path **80** may iteratively pass through a point in space multiple times. It may be appreciated that printing path **80** may include overlapping closed loops such that concrete extrudates are formed on top of previously concrete extrudate layers.

[0066] **Figs. 3A** and **3B** illustrate an embodiment of an apparatus **200** according to the present disclosure. The apparatus **200** includes a housing **210** coupleable to the actuator **300** via a coupler **320**. The actuator **300** is configured to move the apparatus **200** along the printing path **80** and to rotate the apparatus **200** about a main axis **226**. The apparatus **200** is configured to be moveable by the actuator **300** to undergo a movement along a curvilinear printing path **80**, wherein the movement includes translational movement concurrent with rotational movement about the main axis **226**. The housing **210** defines a main nozzle **220** and a first peripheral nozzle **230** disposed adjacent to the main nozzle **220**. The main nozzle **220** is configured to extrude a concrete printing material to form a concrete extrudate **60**. The first peripheral nozzle **230** is configured to extrude a first bonding agent to form a first bonding agent extrudate **70**. The first peripheral nozzle **230** and the main nozzle **220** are configured to undergo rotational movement about the main axis **226** as a rigid body.

[0067] In an example, the first peripheral nozzle **230** is disposed adjacent to the main nozzle **220** with an offset **223** (OS) therebetween (e.g., as shown in **Fig. 4A** or **Fig. 4B**). The apparatus **200** is configured to allow the concrete extrudate **60** and the first bonding agent extrudate **70** to be deposited one ahead of the other, without any obstruction to the concrete printing process. The concrete extrudate **60** and the first bonding agent extrudate **70** can be controllably printed in alignment with one another, and in alignment with the printing path **80**. In some embodiments, as schematically illustrated in **Fig. 4A**, the concrete extrudate **60** is deposited ahead of the first bonding agent extrudate **70**. While the deposition of the concrete extrudate **60** and the first bonding agent extrudate **70** may be timewise occurring simultaneously or concurrently, spatially the concrete extrudate **60** is deposited ahead of the first bonding agent **70**. In other words, relative to the printing path **80**, the concrete extrudate **60** is deposited ahead of the first bonding agent extrudate **70**. The first bonding agent extrudate **70** is laid atop the concrete extrudate **60**, such that the printed first bonding agent

extrudate **70** may be in alignment with both the current layer of concrete extrudate **60** and the next printed layer of concrete extrudate. That is to say, a centerline **70a** defined by the first bonding agent extrudate **70** and a centerline **80a** defined by the concrete extrudate **60** are substantially parallel to one another or the printing path **80**. The printed first bonding agent extrudate **70** may be sandwiched between the current layer of concrete extrudate **60** and the next/subsequently printed layer of concrete extrudate.

[0068] In other embodiments, as schematically illustrated in **Fig. 4B**, the concrete extrudate **60** is deposited behind that of the first bonding agent extrudate **70**, relative to the printing path **80**. The first bonding agent extrudate **70** is deposited atop a previously deposited layer of concrete extrudate **60b**. The first bonding agent extrudate **70** may be aligned with and sandwiched between the current layer of concrete extrudate **60** and the previously (and most recently) deposited layer of concrete extrudate **60b**.

[0069] As shown in **Fig. 4A**, the apparatus **200** illustrates the first peripheral nozzle **230** coupled to the main nozzle **220** at a trailing side **225** of the main nozzle **220**. The apparatus **200** is in a first configuration in which the main nozzle **220** is configured to spatially travel ahead of or in front of the first peripheral nozzle **230** along the printing path **80**. The first peripheral nozzle **230** may be configured to be disposed adjacent or proximal to a trailing side **225** of the main nozzle **220**, in which the trailing side **225** is defined with reference to the printing path **80**. In this first configuration, the apparatus **200** is configured to deposit the concrete extrudate **60** along the printing path **80** ahead of depositing the first bonding agent extrudate **70**. In the first configuration, the first bonding agent extrudate **70** is deposited atop the top surface of the concurrently laid concrete extrudate layer **60**. Upon depositing the first bonding agent extrudate **70**, the first bonding agent extrudate **70** is compressed or spread apart by a subsequent layer of concrete extrudate **60a**. For a bonding agent with a lower viscosity, the bonding agent extrudate may first flow under gravity to spread across the concrete extrudate **60**. The first bonding agent extrudate **70** may be formed substantially in line with the printing path **80**, or in other words, the first bonding agent extrudate **70** may be laid on or applied generally at a center of the concrete extrudate layer **60**. In the first configuration, there is a time interval between the printing of the first bonding agent extrudate **70** and the printing of a subsequent layer of concrete extrudate **60a** (to be stacked atop the printed first bonding agent **70**). The first configuration may be selected to

allow for a longer hardening/setting time to lapse between depositing the first bonding agent and depositing a subsequent layer of concrete extrudate. This enables more control over the hardening/setting time for increasing interlayer bond strength. In some embodiments, for example, where the bonding agent properties or effect do not vary or deteriorate quickly upon deposition, the first configuration may be employed.

[0070] As shown in **Fig. 4B**, the apparatus **200** illustrates the first peripheral nozzle **230** coupled to the main nozzle **220** at a leading side **227** of the main nozzle **220**. The apparatus **200** is in a second configuration in which the first peripheral nozzle **230** is configured to travel in front of or ahead of the main nozzle **220** along the printing path **80**. The first peripheral nozzle **230** may be configured to be disposed adjacent or proximal to a leading side **227** of the main nozzle **220**, in which the trailing side **227** is defined with reference to the printing path **80**. In this second configuration, the apparatus **200** is configured to deposit the concrete extrudate **60** along the printing path **80** behind (after and on top of) the first bonding agent extrudate **70**. In the second configuration, the first bonding agent extrudate **70** is deposited atop a top surface of a previously (and most recently) deposited concrete extrudate layer **60b**. The subsequent layer (currently deposited layer) of concrete extrudate **60** is thus deposited after the first bonding agent extrudate **70** is deposited. Upon laying down the first bonding agent extrudate **70**, the first bonding agent extrudate **70** is immediately compressed, at least partially redistributed or otherwise spread by the layer of concrete extrudate **60**. The second configuration may be selected in some examples, for example, if the first bonding agent extrudate **70** requires a relatively shorter hardening/setting time for a desired interlayer bond strength. The second configuration may also be useful in some embodiments where the first bonding agent extrudate **70** is time sensitive, for example, where the bonding agent properties or interlayer bonding effect varies or deteriorates relatively quickly upon deposition.

[0071] In some instances, the apparatus **200** may be configured such that the first bonding agent extrudate **70** may be deposited “off-center” relative to a center of the subsequent and/or previously laid concrete extrudate layer **60** (e.g., **70b** as shown in **Fig. 7A**), forming an off-center distance between where the first bonding agent extrudate **70** and the concrete extrudate layer **60** first contact the previously laid layer.

[0072] In one example, an outlet **222** of the main nozzle **220** is configured to be larger relative to an outlet **232** of the first peripheral nozzle **230**. Thus, the first bonding agent extrudate **70** has a width smaller than a width of the concrete material extrudate **60**. This ensures the first bonding agent extrudate **70** does not spread exterior to an exterior of the concrete extrudate, thus resulting in a change in surface finish or a change in cross-sectional shape of the printed structure. In other examples, where the first bonding agent may be highly viscous and hence exhibits minimal flow upon extrusion, the first bonding agent extrudate **70** may be configured with a width about equal to a width of the concrete material extrudate **60**.

[0073] In some embodiments, as the first bonding agent is deposited with the aid of gravitational force, the size of the outlet **232** of the peripheral nozzle **230** is determined based on a viscosity of the first bonding agent. For example, a highly viscous first bonding agent (such as cement paste) may require a larger outlet of the peripheral nozzle **230** (for example, 15 millimeters) in comparison to an outlet (for example, 6 to 8 mm) for a less viscous first bonding agent (such as a polymer solution). In other embodiments, the bonding agent forms a viscous bonding agent extrudate which exhibits minimal flow upon deposition. In one example, the bonding agent is a cement paste with 0.26 water-to-cement ratio. In another example, the cement paste includes a superplasticizer (such as ADVA 181N) with 0.35 weight percentage of cement content.

[0074] Similarly, the size of an outlet **222** of the main nozzle **220** may also be determined based on a viscosity of the flowable concrete printing material. As an example, a more viscous concrete printing material may require a larger outlet of the main nozzle **220** in comparison to a less viscous flowable concrete printing material. As an example, the main nozzle **220** may include a polygonal outlet, such that the main nozzle **220** is configured to form a polygonal concrete extrudate, i.e., a concrete extrudate having a polygonal cross section. In another example, the polygonal outlet may be configured with a rectangular outlet, such that the resulting concrete extrudate has a substantially rectangular cross section.

[0075] In an embodiment, the housing **210** is configured to be selectively coupleable (releasably engageable) to the actuator **300** in either the first configuration or the second configuration. For example, the housing **210** may initially be coupled to the actuator in one

configuration, then decoupled from the actuator **300**, and the same housing **210** may be reattached to the same actuator in the other configuration. Therefore, according to various operational considerations, such as the above-described, the housing **210** may be either coupled to the actuator **300** in the first configuration, or alternatively in the second configuration. In this embodiment, once the housing **210** is coupled to the actuator **300** in either of the first configuration or the second configuration, the housing **210** remains in the selected configuration throughout the printing process.

[0076] In another embodiment, the housing **210** is configured to be rotatably coupleable to the actuator **300**. This enables the apparatus **200** to be rotated relative to the actuator **300** between the first configuration and the second configuration, i.e., the apparatus **200** may be rotatable to any position between and inclusive of the first configuration and the second configuration. As an example, the actuator **300** may be configured to rotate the apparatus **200** along the curved portion **80b** of the printing path **80**. This enables the apparatus to form a curved concrete extrudate and a curved first bonding agent extrudate **70** along the curved portion **80b**.

[0077] As shown in **Figs. 5** and **6**, the housing **210** further defines a main channel **224** in fluid communication with the main nozzle **220**. The main channel **224** may be disposed in line with the main nozzle **220** along a main axis **226**. The main channel **224** is configured to receive a flowable concrete material from a concrete source **410** and to deliver the flowable concrete material to the main nozzle **220**. The main channel **224** thus acts as a conduit to flow the flowable concrete material from the concrete source **410** to the outlet **222** of the main nozzle **220**. In another example, the main channel **224** may be disposed forming an oblique angle with the main axis **226**.

[0078] Further, the housing **210** also defines a first peripheral channel **234** in fluid communication with the first peripheral nozzle **230**. The first peripheral channel **234** is configured to receive the first bonding agent from the first bonding agent source **430** and deliver the first bonding agent to the outlet **232** of the first peripheral nozzle **230**. The first peripheral channel **234** may be configured as an annular channel surrounding the main channel **224**. In one embodiment, the first peripheral channel **234** is configured as a funnel. The funnel **234** includes a receiving opening **236** substantially larger than the outlet **232** of

the first peripheral nozzle **230**. The funnel **234** defines sloped portions **234a** configured to facilitate delivery of the first bonding agent via gravity, such that the first bonding agent in the funnel **234** may be substantially uniformly distributed about the first peripheral nozzle **230**. This provides a substantially uniform fluid pressure to the first bonding agent in the funnel **234** and allows a consistent first bonding agent extrudate to be formed by the first peripheral nozzle **230**.

[0079] The apparatus **200** is further provided with a flow splitter **241** in fluid communication with the first bonding agent source **430**. The flow splitter **241** has two flow outlets **242** disposed diametrically on opposing sides of the main channel **224**. The two flow outlets **242** are configured to direct the first bonding agent from the first bonding agent source **430** into respective distinct regions **236a/236b** of the receiving opening **236**. This allows the first bonding agent to be uniformly delivered to the first peripheral channel **230** regardless of the configuration of the apparatus **200**, therefore allowing uniform distribution of first bonding agent within the first peripheral channel **230**. The funnel **234** enables a more uniform delivery of the first bonding agent despite the different respective distances from each of the flow channels **242** to the first peripheral channel **230**. The concrete delivery speed and the bonding agent conveying speed is coordinated such that the concrete deposition and the bonding agent deposition may be in a synchronized manner. In other embodiments, the flow splitter **241** may have more than two flow outlets, for example, a total of six flow outlets. The six flow outlets may be distributed symmetrically about the main axis **226** defined by the main channel **224**.

[0080] **Fig. 7A** illustrates the apparatus **200** navigating a curved portion of the printing path **80b**. It can be seen that the concrete extrudate **60** follows the printing path **80b** with a first radius (R_1), while the first bonding agent extrudate follows a second printing path **70a** with a second radius (R_2). The apparatus **200** includes a rectangular outlet configured to lay a corresponding rectangular concrete extrudate as shown in **Fig. 7B**. The printing path **80b** and second printing path **70a** may form a printing offset **70b** between the first bonding agent extrudate **70** and the concrete extrudate layers **60**. For the purposes of the present disclosure, the printing path **80b** and the second printing path **70** are described as being aligned or in alignment (that is, they are substantially parallel). In one aspect, the printing path **80b** and the second printing path **70a** are substantially parallel for most if not all of the printing path

80b. In another aspect, the first bonding agent **70** is wholly deposited within an area covered by the concrete extrudate **60**. In some examples, the outlet **232** of the first peripheral nozzle **230** may be configured smaller and closer to the main nozzle **220**, for example, when a smaller printing offset **70b** is desired. In other examples, the outlet **232** may be provided with a larger cross-sectional area to enable a suitable flow rate for a more viscous first bonding agent. The concrete deposition and the bonding agent deposition is synchronized in real-time 3D concrete printing, which also provide enhanced interlayer bond strength.

[0081] **Fig. 7C** illustrates the apparatus **200** navigating a curvilinear printing path **80b**. It can be seen that the apparatus **200** concurrently undergoes both a translation **82** and a rotation **84** about the main axis, to move along the curvilinear printing path **80b**. The apparatus **200** concurrently deposits the concrete extrudate along the curvilinear printing path **80b** and deposits the bonding agent extrudate along the second printing path **70a**. **Fig. 7D** further illustrates the apparatus **200** undergoing a rotation **86** to switch from the first configuration in which the main nozzle **220** is configured to travel ahead of or in front of the first peripheral nozzle **230** along the printing path **80**, to the second configuration in which the first peripheral nozzle **230** is configured to travel in front of or ahead of the main nozzle **220** along the printing path **80**.

[0082] **Fig. 8** shows an alternative embodiment in which the funnel **234** is sealed or closed **239** to form a hydraulic slip ring **239**. The hydraulic slip ring **239** defines a chamber **238** to receive the first bonding agent from the first bonding agent source **430** via one or more flow outlets **242**. The chamber **238** may be pressurized to facilitate extrusion of the first bonding agent from the chamber **238** via the first peripheral nozzle **230**.

[0083] **Fig. 9** shows an embodiment of the apparatus **200** coupled to the actuator **300** in which the first peripheral nozzle is partially recessed into a leading side or a trailing side of the main nozzle **220**, with the first peripheral nozzle ending at a higher elevation than the main nozzle.

[0084] **Figs. 10 and 11** show another embodiment of in which the apparatus **200** includes a first spreader **240** disposed adjacent to the first peripheral nozzle **230**. As shown, the main nozzle **220** and the first spreader **240** are disposed on opposing sides of the first peripheral nozzle **230**. In other words, the first peripheral nozzle **230** is disposed between the main

nozzle **220** and the first spreader **240**. The first peripheral nozzle **230** may be disposed proximal to the trailing side **225** of the main nozzle **220**. Upon deposition of the first bonding agent from the first peripheral nozzle, the first spreader **240** follows to level off and/or redistribute the first bonding agent extrudate **70** on a top surface of the concrete extrudate **60**. The first spreader **240** is configured as a trailing spreader in this example. The first spreader **240** may be configured with a leveling surface **246** to spread or redistribute the first bonding agent extrudate **70**, on a selected surface of the concrete extrudate, immediately following or concurrently with the deposition of the first bonding agent extrudate **70**. The leveling surface **246** of the spreader **240** may be arranged at a higher elevation than a rim **228** of the main nozzle **220**. For the sake of convenience, a datum **85** may be defined as a plane coincidental surface on which the current extrudates are printed on. In this example, the datum can be defined at a lower surface of the concrete extrudate. The peripheral nozzle **230** may be located at a higher elevation relative to the leveling surface **246** of the spreader **240**.

[0085] **Figs. 12 to 14** illustrate an alternative embodiment with the apparatus **200** coupled to the actuator **300** in the second configuration. In addition to the main nozzle **220** and the first peripheral nozzle **230**, the apparatus **200** further includes a first spreader **240** disposed adjacent to the first peripheral nozzle **230**. As shown, the main nozzle **220** and the first peripheral nozzle **230** are disposed on opposing sides of the first spreader **240**, or in other words, the first spreader **240** is disposed between the main nozzle **220** and the first peripheral nozzle **230**. The first spreader **240** is configured to spread out or redistribute the first bonding agent extrudate **70** on a selected surface of the concrete extrudate, immediately after or concurrently with the deposition of the first bonding agent extrudate **70**. In this example, the first spreader **240** is configured as a leading spreader. The leveling surface **246** of the spreader **240** may be arranged at a higher elevation than a rim **228** of the main nozzle **220**. For the sake of convenience, a datum **85** may be defined as a plane coincidental surface on which the current extrudates are printed on. In this example, the datum can be defined at a lower surface of the first bonding agent extrudate or an upper surface of a previous layer of concrete extrudate. The peripheral nozzle **230** may be located at a higher elevation relative to the leveling surface **246** of the spreader.

[0086] **Figs. 15A and 15B** are images taken of a cross sections of a specimen of a printed

structure. The printed structure was made using a viscous material such as a cement paste as a bonding agent between layers of concrete extrudates. Cement paste is widely adopted in the construction industry as a cost-effective bonding agent. However, due to the relatively high viscosity of cement paste, an upper surface of the cement paste extrudate tends to show a relatively small radius of curvature, with the cement paste having a tendency to form a tube-like extrudate, even when under the pressure of the subsequent concrete extrudate layer. Defects (as pointed out in **Fig. 15B**) can be found at the interfaces between the cement paste and the concrete extrudates, adversely affecting interlayer bond strength.

[0087] **Figs. 15C** and **15D** are images taken of a cross section of a specimen of another printed structure, 3D printed using the apparatus **200** according to an embodiment of the present disclosure. In this experiment, cement paste was used as the first bonding agent. The cement paste was spread substantially evenly across the width of the concrete extrudate by the spreader **240**. No defects were observed either in the first bonding agent extrudate, or at the interfaces between the first bonding agent extrudate and the concrete extrudate. This is consistent with a structure having a higher interlayer bonding strength. Additionally, the overall profile of the concrete extrudate also improves with the use of the apparatus **200** of the present disclosure.

[0088] **Fig. 16** shows a plot of the relative bond strength of a structure 3D printed using an embodiment of the present disclosure (using a spreader with cement paste as the bonding agent), compared to that of a conventionally 3D printed reference specimen. The relative bond strength of specimens formed using an apparatus according to an embodiment of the present disclosure is higher (267%) compared to the reference specimen (100%). The results confirm that embodiments of the present disclosure provide improvements in the interlayer bonding strength.

[0089] **Figs. 17** and **18** illustrate another embodiment of an apparatus **500**. The apparatus **500** includes a housing **510** coupleable (releasably engageable) to the actuator **300**. The housing **510** defines a main nozzle **520** configured to extrude a concrete printing material to form a concrete extrudate **60**. The apparatus **500** includes a first peripheral nozzle **530** and a second peripheral nozzle **550**. The first peripheral nozzle **530** and the second peripheral nozzle **550** are disposed on opposing sides of the main nozzle **520**. In one example, the main

nozzle **520**, first peripheral nozzle **530** and the second peripheral nozzle **550** are disposed in line with the printing path **80**. The first peripheral nozzle **530** is configured to extrude a first bonding agent to form a first bonding agent extrudate **70**. The second peripheral nozzle **550** is configured to extrude a second bonding agent to form a second bonding agent extrudate **72**. The apparatus **500** is thus configured to deposit the first bonding agent extrudate **70** and the second bonding agent extrudate **72** concurrently ahead of and following the concrete extrudate **60**.

[0090] Further, as illustrated in **Fig. 17**, the housing **510** further defines a first peripheral channel **534** in fluid communication with the first peripheral nozzle **530** and the second peripheral nozzle **550**. The first peripheral channel **534** is configured to receive the first bonding agent from the first bonding agent source **430** via a pair of flow outlets **542**. The first bonding agent is delivered to the first peripheral nozzle **530** and the second peripheral nozzle **550**, and extruded to form the first bonding agent extrudate **70** and second bonding agent extrudate **72**. The first peripheral channel **534** may be configured as an annular channel. In an embodiment, the first peripheral channel **534** is configured as a funnel.

[0091] Alternatively, as illustrated in **Fig. 19**, the housing **510** further defines a first peripheral channel **534** in fluid communication with the first peripheral nozzle **530**; and a second peripheral channel **554** in fluid communication with the second peripheral nozzle **550**. The first peripheral channel **534** is configured to receive the first bonding agent from the first bonding agent source **430** via a first flow outlet **544**. The first bonding agent is delivered to the first peripheral nozzle **530** to be extruded to form the first bonding agent extrudate **70**. The second peripheral channel **554** is configured to receive a second bonding agent from a second bonding agent source via a second flow outlet **546**. The second bonding agent is delivered to the second peripheral nozzle **550** to be extruded to form the second bonding agent extrudate **72**. The apparatus **500** is configured to deposit the first bonding agent extrudate **70** and the second bonding agent extrudate **72** concurrently ahead of and behind that of the concrete extrudate **60**. In this embodiment, the second bonding agent may have a different chemical composition from the first bonding agent. Therefore, the second bonding agent extrudate **72** have a different chemical composition from the first bonding agent extrudate **70**. In some embodiments, the first bonding agent extrudate **70** and the second bonding agent extrudate **72** are configured to react chemically to form a strong

interlayer bonding agent extrudate.

[0092] In another embodiment of the apparatus **500**, as shown in **Fig. 20**, the apparatus **500** further includes a first spreader **540** disposed adjacent to the first peripheral nozzle **530**; and a second spreader **560** disposed adjacent to the second peripheral nozzle **550**. The main nozzle **520** is disposed between the first spreader **540** and the second spreader **560** along the printing path **80**. The first spreader **540** is configured to spread the first bonding agent extrudate **70** concurrently with the deposition of the first bonding agent extrudate **70**. The first spreader **560** is configured to spread the second bonding agent extrudate **72** concurrently with the deposition of the second bonding agent extrudate **72**. In some embodiments, the first bonding agent extrudate **70** have a different composition from the second bonding agent extrudate **72**. As an example, they may be configured to chemically react to form a bonding agent extrudate.

[0093] **Fig. 21** is a schematic flow diagram of a method **900** of concrete additive manufacturing (3DCP) according to embodiments of the present disclosure. The method **900** includes extruding **910** a concrete material via a main nozzle to form a concrete extrudate, the main nozzle defining a main axis; extruding **920** a first bonding agent via a first peripheral nozzle to form a first bonding agent extrudate; and providing a movement of the main nozzle and the first peripheral nozzle along a curvilinear printing path **930**. The movement (of the main nozzle and the first peripheral nozzle) includes a translational movement concurrent with a rotational movement about the main axis, and wherein the movement is concurrent with the extruding of the flowable concrete material and the extrusion of the first bonding agent. The first peripheral nozzle and the main nozzle may be configured to undergo the rotational movement about the main axis as a rigid body. The method **900** is suitable for use with a flowable concrete material. The method **900** is suitable for use with a first bonding agent that is a viscous material. The method **900** may involve selectively depositing the concrete extrudate ahead of depositing the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a first configuration; or depositing the concrete extrudate behind that of laying the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a second configuration. The method **900** enables depositing the first bonding agent such that the first bonding agent extrudate is deposited parallel to the concrete extrudate, even if the concrete

extrudate is being extruded via a rectangular outlet of the main nozzle. The method 900 may include spreading or distributing the first bonding agent extrudate on a selected surface of the concrete extrudate. The first bonding agent extrudate may be spread or distributed concurrently with the movement of the main nozzle and the first peripheral nozzle.

[0094] Due to the nature of 3DCP in which each concrete extrudate layer is extruded atop a previously extruded concrete layer, the interlayer bond strength between the interfaces of the extrudates is one of the factors determining the overall integrity and strength of the final concrete structure. While the interlayer bond strength may be improved by the provision of a bonding agent between layers of concrete extrudates, it has been shown that bonding agents may themselves contribute to the formation of defects and negatively impact both the overall interlayer bond strength as well as the overall profile of the concrete structure. The apparatus and method according to any of the embodiments of the present disclosure described herein advantageously address these technical challenges such that improved interlayer bonding strength can be achieved. The apparatus disclosed herein may be used with various types of extrudates and bonding agents. Even in cases where the bonding agent has a relatively low viscosity, the present apparatus can facilitate a more accurate application of the bonding agent. In one aspect, the bonding agent can be applied in a more selective or targeted manner, such that the bonding agent extrudate is aligned with the concrete extrudate, relative to the printing path, even if the printing path requires continuous printing around a corner or along a curvilinear path. In another aspect, the bonding agent can be applied in a more selective or targeted manner to coat only the upper and/or lower surfaces of opposing surfaces of the extrudates. This would be an improvement over indiscriminate spraying of bonding agents via a jet/spray on all surfaces of the extrudate as there will be significantly less wastage. A more targeted and controlled application of the bonding agent also avoids problems associated with the bonding agent affecting surface quality of the side surfaces of the concrete extrudate, e.g., the surface quality of a wall of a building structure. Further, embodiments of the apparatus of the present disclosure are also suitable for use with flowable materials with different viscosities, even in combination with bonding agents with relatively higher viscosities, such as cement paste.

[0095] All examples described herein, whether of apparatus, methods, materials, or products, are presented for the purpose of illustration and to aid understanding, and are not

intended to be limiting or exhaustive. Various changes and modifications may be made by one of ordinary skill in the art without departing from the scope of the invention as claimed.

CLAIMS

1. An apparatus for concrete additive manufacturing, the apparatus comprising:
 - a housing coupleable to an actuator, the housing defining:
 - a main nozzle defining a main axis, the main nozzle being configured to extrude a flowable concrete material to form a concrete extrudate; and
 - a first peripheral nozzle disposed adjacent to the main nozzle, the first peripheral nozzle configured to extrude a first bonding agent to form a first bonding agent extrudate, wherein the housing is configured to be moveable by the actuator to undergo a movement along a curvilinear printing path, wherein the movement includes a translational movement concurrent with a rotational movement about the main axis.
2. The apparatus as recited in claim 1 wherein the first peripheral nozzle and the main nozzle are configured to undergo the rotational movement about the main axis as a rigid body.
3. The apparatus as recited in any of claim 1 or claim 2, wherein the first peripheral nozzle is coupled to the main nozzle at one of a leading side and a trailing side of the main nozzle.
4. The apparatus as recited in any of the above claims, wherein the first bonding agent is a viscous material.
5. The apparatus as recited in any of the above claims, wherein the apparatus is configured to:
 - selectively deposit the concrete extrudate ahead of depositing the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a first configuration; or
 - selectively deposit the concrete extrudate behind that of laying the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a second configuration.

6. The apparatus as recited in any of the above claims, wherein the first bonding agent extrudate has a width smaller or equal to a width of the concrete material extrudate.
7. The apparatus as recited in any of the above claims, wherein the first bonding agent extrudate is formed substantially in line with the printing path.
8. The apparatus as recited in any of the above claims, wherein the first bonding agent extrudate is deposited parallel to the printing path.
9. The apparatus as recited in any of the above claims, wherein the main nozzle is configured with a polygonal outlet.
10. The apparatus as recited in claim 9, wherein the polygonal outlet is a rectangular outlet.
11. The apparatus as recited in any of the above claims, wherein the housing is configured to be rotatably coupleable to the actuator, wherein the apparatus is rotatable about the main axis.
12. The apparatus as recited in any of the above claims, further comprising a first spreader disposed adjacent to the first peripheral nozzle, wherein the first spreader is configured to redistribute the first bonding agent extrudate.
13. The apparatus as recited in claim 12, wherein the first bonding agent extrudate is spread on a selected surface of the concrete extrudate.
14. The apparatus as recited in claim 12 or claim 13, wherein the main nozzle and the first spreader are disposed on opposing sides of the first peripheral nozzle.
15. The apparatus as recited in claim 12 or claim 13, wherein the main nozzle and the first peripheral nozzle are disposed on opposing sides of the first spreader.
16. The apparatus as recited in any of the above claims, wherein the housing further defines a main channel in fluid communication with the main nozzle, the main channel being configured to receive the flowable concrete material from a concrete source.

17. The apparatus as recited in claim 16, wherein the housing further defines a first peripheral channel in fluid communication with the first peripheral nozzle, the first peripheral channel being configured to receive the first bonding agent from a first bonding agent source.
18. The apparatus as recited in claim 17, wherein the first peripheral channel is configured as a funnel, the first peripheral channel includes a receiving opening substantially larger than the first peripheral nozzle.
19. The apparatus as recited in claim 17 or claim 18, further comprising a flow splitter, the flow splitter being in fluid communication with the first bonding agent source, the flow splitter having at least two flow outlets, wherein the at least two flow outlets are configured to direct the first bonding agent from a first bonding agent source into respective distinct regions of the receiving opening of the first peripheral channel.
20. The apparatus as recited in claim 19, wherein the distinct regions of the receiving opening are diametrically disposed about the main axis.
21. The apparatus as recited in claim 17, wherein the first peripheral channel is sealingly connected to the first bonding agent source to form a pressurized chamber in the first peripheral channel.
22. The apparatus as recited in claim 17, wherein the housing further defines a second peripheral nozzle configured to extrude a second bonding agent as a second bonding agent extrudate, wherein the second peripheral nozzle and the first peripheral nozzle are disposed on opposing sides of the main nozzle in line with the printing path.
23. The apparatus as recited in claim 22, further comprising a second spreader disposed adjacent to the second peripheral nozzle, wherein the second spreader is configured to redistribute the second bonding agent extrudate.
24. The apparatus as recited in any of claims 22 to 23, wherein the housing further defines a second peripheral channel, the second peripheral channel being in fluid communication with the second peripheral nozzle, and wherein the second

peripheral channel is configured to receive a second bonding agent from a second bonding agent source.

25. The apparatus as recited in claim 22, wherein the second bonding agent is characterized by a different composition from the first bonding agent.
26. A system for concrete additive manufacturing, the system comprising:
 - the apparatus as recited in any of the above claims;
 - an actuator coupled to the apparatus; and
 - an actuator controller configured to control the actuator to move the apparatus along the printing path to lay the concrete extrudate and the first bonding agent extrudate.
27. The system as recited in claim 26, wherein the actuator controller is configured to control the actuator to rotate the apparatus along a curved portion of the curvilinear printing path.
28. The system as recited in claim 26 or claim 27, wherein at least one of the bonding agents is a viscous material.
29. The system as recited in claim 28, wherein at least one of the bonding agents is a cement paste with a 0.26 water-to-cement ratio.
30. The system as recited in claim 28, wherein the at least one of the bonding agents comprises a superplasticizer.
31. A method of concrete additive manufacturing, the method comprising:
 - extruding a flowable concrete material via a main nozzle to form a concrete extrudate, the main nozzle defining a main axis;
 - extruding a first bonding agent via a first peripheral nozzle to form a first bonding agent extrudate; and
 - providing a movement of the main nozzle and the first peripheral nozzle along a curvilinear printing path, wherein the movement includes a translational movement concurrent with a rotational movement about the main axis, and wherein

the movement is concurrent with the extruding of the flowable concrete material and the extrusion of the first bonding agent.

32. The method as recited in claim 31, wherein the first peripheral nozzle and the main nozzle are configured to undergo the rotational movement about the main axis as a rigid body.
33. The method as recited in claim 31 or claim 32, wherein the first bonding agent is a viscous material.
34. The method as recited in any of claims 31 to 33, the method comprising one of:
 - depositing the concrete extrudate ahead of depositing the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a first configuration; and
 - depositing the concrete extrudate behind that of laying the first bonding agent extrudate relative to the printing path, responsive to the apparatus being in a second configuration.
35. The method as recited in any of claims 31 to 34, wherein the first bonding agent extrudate is deposited parallel to the concrete extrudate, the concrete extrudate being extruded via a rectangular outlet of the main nozzle.
36. The method as recited in any of claims 31 to 25, further comprising: spreading the first bonding agent extrudate on a selected surface of the concrete extrudate.
37. The method as recited in claim 36, wherein the first bonding agent is spread concurrently with the movement of the main nozzle and the first peripheral nozzle.